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TERTIARY STRATIGRAPHY AND OROGENY OF THE NORTHERN PUNJAB[1]

BY ROBERT VAN VLECK ANDERSON

(Presented in abstract before the Cordilleran Section of the Society)

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SUMMARY

The Tertiary of the Punjab is divided into two principal parts, the marine and estuarine Eocene (Nummulitic) system below and, unconformably overlying this, a great succession of nonmarine beds representing continental sedimentation from the Oligocene to the late Pliocene or early Quaternary. This nonmarine succession, here named the "Nimadric System," [illegible] Murree and Siwalik series. It comprises over 20,000 feet of [illegible] stratified alternating sandy and silty beds, mainly fine-grained [illegible] conglomeratic in its uppermost division. It is interpreted as the product of mainly fluviatile, but in part eolian, deposition over fairly flat plains, under a semitropical climate of medium rainfall. The plains extended into the region now occupied by the Himalaya. Evidence of the validity of thickness measurements is afforded by the comparative constancy of individual fine-grained formations, the great thicknesses superimposed in single sections, and by the record here presented of a well 6,000 feet deep. The Nimadric system is divisible into several stages, representing pulsations in the orogenic sequence. The several divisions of the Nimadric decline in thickness southward away from the Himalayan province, which was the source of most of the material.

Structurally, the region is dominantly one of compressional forces tending to fold and thrust the strata southward. The complexity and severity of deformation in the Tertiary beds is greatest in the Himalayan front ridges and tends to decrease away from the mountains. Evidence is afforded by the character, thickness variation, distribution, and structure of the beds that mountain-building and sedimentation during the period following the emergence of the Nummulitic from the widespread Eocene sea went on as follows:

a. Gentle upwarping and wearing down of the Nummulitic in a period preceding that of the oldest known beds of the Nimadric system.

b. Progressive building up of the ancestral Himalayan range, commencing scores of miles north of the present front ridges.

c. Gradual southward encroachment of the mountains by means of overfolding and thrusting, presumably involving from time to time new segments of the submontane province on the south.

d. Progressive downtilting of the plains sector, with greatest subsidence adjoining the mountain front, but with aggradation keeping the surface level constant.

e. Concurrent southward transgression of the basin of deposition of the system.

f. Pronounced rejuvenation and encroachment of the mountains toward the close of Middle Siwalik time; and, finally,

g. Strong deformation during the Quaternary, commencing possibly in the late Tertiary, affecting all portions of the system and producing the structures now in evidence.

The Salt Range was gently elevated after the Eocene, and so remained [illegible] some time in the Miocene; [illegible] subsided as part of the basin of [illegible] of the [illegible] beds, and [illegible] rose during the later Tertiary and [illegible] Quaternary and transgressed for many miles southward [illegible] means of low-angle thrusting of Cambrian and later beds on the Tertiary.

INTRODUCTION

The region here discussed is that portion of northwestern India comprising the Salt Range and the plateau-like area to the north of it, called the Potwar, together with the ridges some 70 miles north of the Salt Range, which bound the Potwar Plateau on the north and which are referred to in this paper as the front or outer ridges of the Himalaya. The material presented is based on observations made during several years' work in this region by the geologists of the Whitehall Petroleum Corporation, Limited, of London, whose directors have kindly permitted the publication of this paper.

The purpose of the paper is primarily to put on record the section penetrated by the 6,000-foot "Jhatla" well drilled by the corporation, to describe in a summary way the great continental Tertiary system in which this well was drilled, and to draw certain inferences as to the conditions that must have prevailed during the time that this thick succession was being formed.

The geologists whose field-work contributed materially to the information here presented were the following: Dr. B. R. MacKay, who spent two seasons as chief of a field party in the region here dealt with and whose reports have been a principal source of reference in preparing this paper; Mr. D. Dale Condit, who since 1921 has been the corporation's chief geologist in India; Mr. J. M. Weller, who was assistant to Dr. MacKay and aided him in the preparation of reports; Mr. W. F. Eastman, who kept the log of the Jhatla well during most of the long drilling period and also made numerous careful section measurements; Dr.

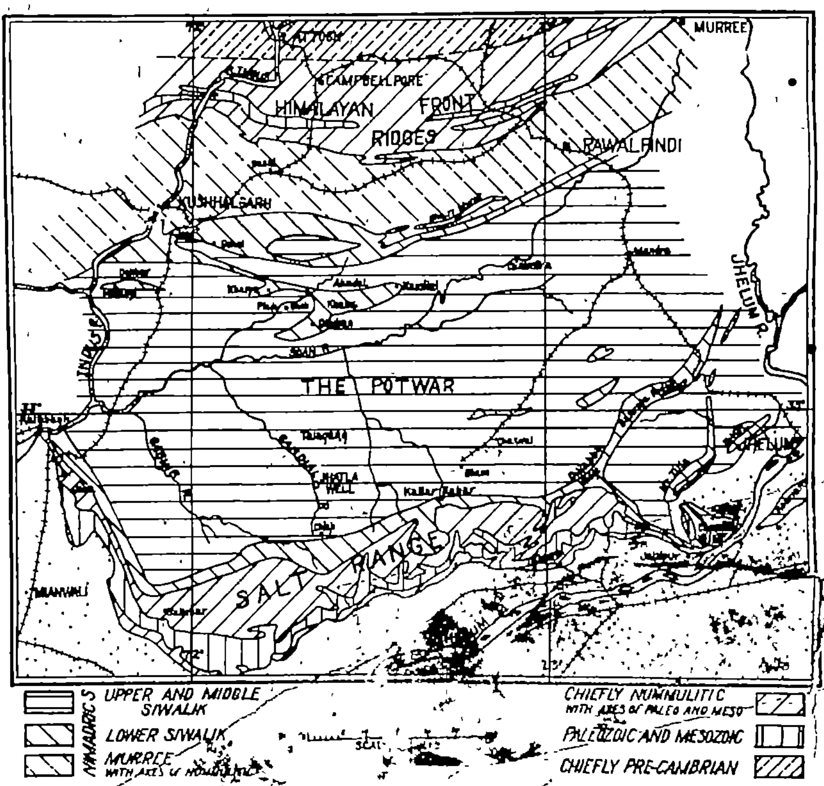

FIGURE 1.—Generalized Map of Portion of Northern Punjab

J. J. O'Neill, who was chief of a field party in this region for a season; and Mr. J. R. Cox, who spent the greater part of a year in the field. The writer made reconnaisances in the region during the winter of 1920-1921 and again in 1925 and was in touch with the work throughout.

The geology of the Salt Range, the Potwar Plateau, and the outer Himalaya has been the subject of numerous important publications, but the present writer, intending this paper only as a summary based on field surveys, has not attempted a critical review of previous work and conclusions, nor to make a compilation of information from the literature. Possession of the results of earlier workers was of distinct help in carrying out studies in the Punjab, and particular mention should be made of the excellent pioneer work and maps of Wynne.[2] Among other valuable contributions are the papers by Dr. G. E. Pilgrim[3] on the stratigraphy and vertebrate remains; Notes on structure and stratigraphy in the Northwest Punjab by E. S. Pinfold,[4] and Dr. E. H. Pascoe's treatise on Petroleum in the Punjab and Northwest Frontier Province.[5] The latter contains a good bibliography.

Tertiary sedimentary beds occupy most of the region here discussed and comprise the two main divisions which constitute the Tertiary in northwestern India, namely, the Eocene, or "Nummulitic," system and the prodigiously thick nonmarine system, which represents much, if not all, of the Tertiary subsequent to the Eocene, and possibly also part of the Quaternary. There is a notable scarcity of igneous rock both in the Cenozoic and in the older groups, which extend back to the early Paleozoic.

EOCENE SYSTEM

GENERAL STATEMENT

The Eocene system is partially represented in this general region by a Nummulitic series, varying up to over 2,500 feet in thickness, composed of marine limestone, shale, and calcareous sandstone, with considerable bodies of estuarine and evaporation-basin deposits. The latter types appear particularly in the upper portion and seem to represent in a striking way the variable conditions of inclosed arms of the sea during the marine retreat from this portion of the continent. The stratigraphy of the series has not been thoroughly worked out, but the subdivisions generally accepted in this region, and which appear to hold good here, are a lower and an upper division, as summarily described below.

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[2] Memoirs and records of the Geol Survey of India, 1870 to 1880.

[3] Rec. Geol. Surv. Ind., 1910 *et seq.*

[4] Rec. Geol. Surv. Ind., vol. xlix, 1918.

[5] Mem. Geol. Surv. Ind., vol. xl, Part 3, 1920.

LOWER DIVISION

The lower division of the Nummulitic, frequently referred to as the "hill limestone" because of its prominent part in forming the outer ridges of the Himalaya and the plateau-like summit of the Salt Range, consists principally of massive limestone, interbedded—particularly in its lower portion—with dark shale, variegated sandstone, and locally coaly beds. Its thickness in the front ridges of the Himalaya is reported to be over 1,800 feet, whereas in the Salt Range it has a maximum thickness of 700 feet in the western portion of the range, not far from the Indus. Thence eastward in the Salt Range its thickness progressively declines, until in the ridges that project from the eastern end of the range, toward the Jhelum River, it displays only isolated remnants, and the post-Eocene beds were deposited in places directly on Cretaceous or older strata.

UPPER DIVISION

The upper portion of the Nummulitic of this region, named the "Chharat" by Pinfold, is composed largely of purplish, greenish, and otherwise variegated gypsiferous clay shale and calcareous shale, interbedded with usually thin beds of limestone and fine quartzitic sandstone. A striking feature is afforded by shaly limestone beds composed of a mass of nummulite shells. The above are the characteristics as displayed in the main belt of outcrop of this division along the northern border of the Potwar Plateau.

Another main belt of outcrop, of beds probably the equivalent, and consisting of brick-red, pinkish, purplish, white, and variegated highly gypsiferous and saline clays, calcareous and dolomite shale, etcetera, with huge masses of rock-salt and gypsum, occurs almost all along the southern foot of the Salt Range. These constitute the famous "salt marls" which gave the name to the range and were formerly believed to be Paleozoic or older because they underlie beds of early Paleozoic age. As inferred by several later writers, however, and as shown below, they are with little doubt part of the Nummulitic series beneath a huge overthrust.[6]

In the northern belt the upper division of the Nummulitic series comprises a thickness, as recorded by Pinfold, of about 500 to 900 feet. In the "salt marl" belt the thickness is difficult to determine, owing to surface incrustation and because the base is hidden beneath the plains, but it appears to be considerably over 1,000 feet. The salt mines reveal individual beds of pure salt over 100 feet thick and the aggregate of pure and impure salt deposits amounts to several hundred feet.

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[6] An interesting discussion of this and hypothetical alternatives to explain the puzzling problem of the "saline series" and its position is given by Pascoe in his memoir previously cited.

PROOF OF SALT RANGE OVERTHRUST

The southern escarpment of the Salt Range faces the plains of the Punjab and displays one of the world's most remarkable sections. At the base is the gaily colored mass of the saline stage, and overlying this in successive upward steps, formed by beds dipping moderately northward and excellently exposed, there rises a sequence of diversified sedimentary formations representing numerous periods from the Cambrian to the Miocene. Concordantly beneath the oldest fossiliferous zone (the marine "Neobolus beds," Cambrian), and lying upon the "salt marls" is a zone, several hundred feet thick, called the "purple sandstone." This is undoubtedly the oldest member of the Paleozoic present here. Except for numerous faults, many of which, it is to be noted, are southward thrusts, the upper portion of the "purple sandstone," as well as the higher strata, is little disturbed. In the lower 200 feet or so of the "purple sandstone," however, signs of disturbance progressively increase downward, and the basal 50 to 100 feet is a zone of severe shattering, showing that this horizon has been a locus of crushing and brecciation. The highest portion of the "salt marl" stage immediately below is slickensided and squeezed and the contact is a discordant one. The overlying horizon, in spite of brecciation, is very persistent. The underlying formation is likewise remarkably continuous, but a close examination of the contact between the two shows that the "purple sandstone" zone rides at different points on different horizons of the "salt marls." Moreover, the latter are locally overridden by higher members of the superjacent groups.

These relations indicate that the Paleozoic and Mesozoic mass has been overthrust upon the saline stage. The contact dips northward beneath the Salt Range, approximately parallel with the bedding, but, if anything, at a somewhat lower angle, and is evidently the plane of thrust. The continuity of the "purple sandstone" zone and the "salt marls," one superimposed on the other in such manner along most of the range, gives a strong semblance of a regular stratigraphic sequence and makes this a puzzling and very noteworthy example of bed-thrusting. The fact that the highly incompetent and plastic gypseous and saline deposits would afford an ideal zone for a thrust to be initiated in and to move on doubtless explains in part the persistency with which this formation is the basement beneath the overriding mass.

The Paleozoic and Mesozoic beds, however, do encroach on still later strata toward the eastern end of the Salt Range. Near Jalalpur the "purple sandstone" zone lies with similar attitude on highly disturbed Siwalik beds, in a relation interpreted by the writer as one of overthrust, thus affording confirmatory evidence of the great thrust or, rather, group of thrusts represented by the range, as well as of the conclusion drawn later in this paper from other data, that the thrusting is late Tertiary or Quaternary in age.

In addition to the structural indications above cited, there is evidence that the age of the saline stage is far less than that of the strata overlying. In the gypseous beds below the "purple sandstone," the writer found the following evidences of the posterior age of the "salt marls," and therefore confirmation of the overthrust:

a. Calcareous and siliceous shales closely resembling the organic shales of the Nummulitic series, even though the traces of organisms which doubtless once existed have been obscured by siliceous and dolomitic replacement.

b. Carbonaceous and other shales that could hardly be conceived as having preserved their Tertiary lithologic character had the beds suffered the lapse of time and undergone the degree of induration, moderate though it be, which has affected the Paleozoic strata.

c. A slight impregnation with petroleum, such as characterizes the Nummulitic and is not known in any pre-Tertiary strata in this part of India.

d. Poorly preserved impressions of leaves of a Tertiary or, at earliest, Mesozoic type.

The Tertiary leaves referred to in *d* were found in well-bedded and laminated calcareous shale in the upper part of the saline stage in Kheura Gorge. Dr. Ralph W. Chaney, of the Carnegie Institution, who kindly examined them, writes as follows:

> "The specimen clearly contains fragments of several specimens of dicotyledenous leaves. This places their age as not older than Lower Cretaceous when the first Dicots appeared. One of the leaves is very probably oak *(Quercus)* and its size and margin strongly suggest the Oligocene species *Quercus clarnensis* from western America. It is of interest to note that I found a closely related species in the Oligocene deposits of Manchuria. Your specimen is almost certainly of Tertiary age."

The post-Jurassic age of the basement stage of the Salt Range being thus established, it is clear that the overlying mass of the range has been thrust in a general southward direction on it. The movement along the principal thrust-plane must amount at least to several miles. There also remains no reason to doubt the equivalence of the "salt marls" to the similar deposits of known Eocene age in the Punjab and Northwest Frontier Province, the only reason for doubting this having been their position beneath the Cambrian.

NIMADRIC SYSTEM

The post-Eocene Tertiary is a picturesque, even though somewhat monotonous, alternation of varicolored sandy and silty, and to a lesser extent conglomeratic, beds of a fluviatile character. Whereas the Nummulitic series was formed in an epicontinental marine basin that included much of the area subsequently occupied by the Himalaya Mountains, the thick succession of beds that overlies represents continental sedimentation on plains at the foot of the ancestral Himalayan Range. This range was partly composed of the uplifted Nummulitic, as shown by materials in the overlying beds derived by erosion from that series. The historical and structural break between the Nummulitic and the unconformably overlying strata bears evidence of being the major one in the Tertiary of this part of the world. From their rich vertebrate fauna these subsequent strata have been correlated by Dr. Pilgrim and others with the whole of the Pliocene and Miocene and probably later Oligocene. It seems not unlikely that beds belonging to the same system may be found which date even farther back, and the upper members may reach into the Pleistocene.

Although showing variations in color, mineral grain, and the grouping of beds at different horizons, this post-Eocene succession is essentially one system of deposits of a fairly homogeneous type, representing sedimentation on floodplains under a set of conditions on the whole remarkably constant. Being at least in broad lines a unit, it is awkward not to have a single name for the whole system. The designation "Sub-Himalayan," which was applied to the Tertiary beds by Medlicott and other early geologists in India, would be appropriate as a means of referring to this post-Nummulitic system, owing to the genetic relationship of the deposits to the zone of depression at the southern foot of the great mountain arcs of India. Unfortunately, the term was used to include not only this system, but the Nummulitic as well. It is, therefore, unavailable as a designation for a portion only of the Tertiary sequence.

The name "Nimadric" is here proposed for the whole of the great system in question, which represents the period of continental sedimentation after the withdrawal of the sea from this northern portion of India up to the time near or soon after the close of the Pliocene, when the system as a whole had become folded through the period of major deformation that left it essentially with its present structural outlines. The name is a compound of "Himadri," meaning snowy range (from "hima," snow, and "adri," mountain), with the Sanskrit prefix "ni," meaning under, downward, or nether. The elision of the syllable "hi" is in keeping with similar elisions frequent in Sanskrit. The name "Himadri" was used by the ancients as an alternative for Himalaya (from "hima," snow, and "alaya," abode) and its use in the present context seems appropriate, as suggestive of the ancestral nature of the mountains from which the sediments were derived and at whose foot the system was layed down. It may be noted also that, for reasons brought out more fully later in this paper, the plains over which these sediments were spread must have been situated in part within the latitudes now occupied by the outer Himalayan ridges or ranges. These southern ridges grew in part by involving portions of the plains deposits in the frontal mountain structures and in part by overriding on strata of this system. Thus, in a double sense, the prefix "ni" in the name here given connotes the subjacent relationship that this system bears to the Himalaya and its related ranges, with the Indo-Gangetic border of which these deposits are coextensive.

By present usage different parts of the Nimadric system are referred to by two or more names, the "Siwalik" for the upper portion, representing the period from about mid-Miocene to the end of the Pliocene or later, and, in the particular region here treated, the "Murree" for the lower portion. Southeastward, in the Simla region, the approximate equivalent of the Murree is designated in two divisions—the "Dagshai" below and the "Kasauli" above. No precise line of demarcation is known between lower and upper portions of the Nimadric system, and in the region here treated there appears to be conformable gradation throughout. Such general continuity is probable, notwithstanding the likelihood that this relationship was locally and from time to time disturbed, especially adjacent to the ancestral mountains, by deformational forces affecting the beds while accumulation of the system was going on.

Uplifting of the earlier portion of the system along the mountain border previous to the deposition of the Siwalik is suggested, though not proven, by the failure to find Siwalik beds infolded with the Murree in the compressed structures of the present Himalayan foothills, north of a line between Rawalpindi on the east and the Indus a little north of Kushalgarh on the west. But the Murree may be observed overthrust on the Lower and Middle Siwalik in several areas not far south of that line, and the character of the Siwalik members folded and faulted in with the Murree there is not such as to indicate that this was at all near the northern limit of their basin of deposition. At least the lower and middle divisions of the Siwalik were deposited much farther north, and their absence from view in that direction is to be explained by faulting and by the profound erosion which has truncated the northern region. Hence no unconformable relation between Murree and Siwalik is in evidence. There are suggestions of local unconformable overlap of Upper Siwalik on earlier Siwalik beds, and other features occur lower in the system that may be interpreted as indicating minor unconformities. None of these features, however, is out of harmony with the conception of continuous continental sedimentation within this general period and region of deposition. In the writer's opinion, any unconformities that exist within the system are entirely subordinate in importance to the erosional unconformity of almost continental significance which separates it from the marine Eocene. The basal beds of the system lie variously on different horizons of the Nummulitic series, at least hundreds of feet of the latter having been locally eroded away prior to the deposition of the Murree. In places a slight discordance of dip and truncation of the Eocene beds can be seen at the contact, and there is characteristically a basal zone of the Nimadric system containing subangular fragments derived from the Eocene.

Some of the early workers in Indian geology regarded the Murree series and its equivalents closely related to the Nummulitic beds and conformable with them. The Nummulitic and Murree were therefore grouped together as early Tertiary under the joint name "Sirmur" and set off from the later Tertiary or Siwalik. Among the principal factors leading to this classification apparently were:

a. The close association of the Murree and Nummulitic beds in many compressed structures, making them difficult to separate and giving them the semblance of intimate relationship.

b. A certain similarity in purplish, greenish, and other colors between the Murree and the estuarine phases of the Nummulitic.

c. The occurrence in the lower Murree beds of nummulites derived by erosion from the former series, which led to confusion.

Even though these factors are now known to have no validity as a basis for grouping the two together, the concept, once established and dignified by a name, tends to persist. The name "Sirmur" represents an entirely unnatural grouping and should be discarded. The more natural and significant classification is to group the whole of the continental system together, as done in this paper, and to draw the main line of separation between it and the Nummulitic. A valid basis for this classification is afforded by the major unconformity at the base of the Nimadric, the relative homogeneity and continuity of this system, and finally the essential contrast in the nature and origin of the deposits in the two systems so separated.

The Nimadric system, where measured in the regions of its most complete development, in the northern and central parts of the Potwar Plateau, has a thickness of at least 20,000 feet. In fact, the maximum thickness would appear to be in excess of 23,000 feet. The major lithologic zones are recognizable from place to place and are susceptible of fairly close measurement, owing to the clear stratification between alternating beds of different grain and color. One is inclined to be skeptical of thicknesses when they mount to such huge totals, but a study of the region convinces the observer that the measurements closely represent the true vertical thicknesses and give a reliable gauge of the depth of subsidence in the deeper portions of the basin of deposition. It is inconceivable that strata of these fine-grained types, comprising stages traceable with comparatively consistent lithologic characters over areas of thousands of square miles, could have been deposited otherwise than on fairly flat surfaces, over which each member was widely spread and, in the aggregate, vertically built up. The presence of several or all stages of the system in single steeply tilted and horizontally short sections and their repetition with similar thickness on the opposite flanks of the same structures, as well as in other structures at a distance, gives opportunity for verification of the measurements. And similar verification is afforded on a less extensive scale by occasional vertical sections where the beds are horizontal.

An interesting result of the Jhatla well is the close confirmation which this deep boring gives of the thickness of certain stages as measured on the surface. The well penetrated vertically through nearly 6,000 feet of these beds where they lie almost horizontally, and the thicknesses checked closely with the surface measurements of the same portions of the system made in near-by districts where they are upturned.

One of the most complete sections is to be found within 20 miles southwest of Rawalpindi, on the Khairi-Murat Ridge, and thence southeastward into the valley of the Soan River, where in a distance of 11 to 15 miles across the strike a thickness of 18,000 feet or more may be measured. Here all the major divisions of the Nimadric system are superimposed one on the other. Owing to disturbance of the lower portion, the measurement is not complete, and there is no assurance that the uppermost beds exposed in the Soan Syncline include the youngest members of the system.

A notable feature with relation to these great thicknesses, clearly brought out in successive section measurements southward away from the Himalaya front, is that a progressive thinning of the members takes place in that direction. For instance, the Murree beds, which have an undetermined thickness of at least 5,000 feet, and probably much more, along the border of the mountain province, thin out to the vanishing point within less than 60 miles to the south. Similarly, the Lower Siwalik division thins progressively within a distance of 50 miles from 6,000 feet or more to about 2,700 feet. The middle and upper divisions of the Siwalik also become reduced to the southward, their combined thickness (in single sections) declining from 9,000 feet or more to approximately 6,000 feet within the same distance. Sections of the Siwalik as a whole lose between 40 and 50 per cent of their thickness between the northern and southern parts of the region, and if the reduction of the Murree be added the total loss of thickness may be conservatively stated as more than 10,000 feet.

In the same southward direction a tendency is noted for the average coarseness of the deposits to decline moderately, and for siltstones to assume a somewhat more important rôle in the aggregate. This tends to confirm other evidence that most of the material was derived from the north. However, variations in coarseness also occur laterally and locally, and it would require a very detailed analysis to reconstruct the channels and areas of coarser and finer sedimentation.

A characteristic and well-known feature of the system, and particularly of the Siwalik portion, is the abundant occurrence of fossil vertebrate remains. A great variety of teeth and bones, some of large proportions, are scattered through the sandy beds, and especially in the "pseudo-conglomerate" and true conglomerate zones. A significant feature, indicative of the fluviatile nature of the deposits, is that these remains show the effect of dispersal and wear prior to being buried. Remains of palms and other plants are found scatteringly, generally in a poor state of preservation, this condition being also indicative of comminution by streams rather than deposition of the sediments in quiet bodies of water. Fossil wood is common, especially so in the Kamlial stage of the Lower Siwalik. Further brief reference to the fossils will be made in the section dealing with Tertiary history.

TILTED PLEISTOCENE GRAVEL

A discussion of the various Quaternary deposits is not within the scope of this paper, but mention needs to be made of the fact that there is a formation of fluviatile gravel and boulder beds, referable with little doubt to the Pleistocene, which appear to be unconformable on the Siwalik and which have been, locally at least, considerably deformed, Such beds attain a thickness of several hundred feet. In the zone of deformation, at the southern foot of the hills of Nummulitic limestone and Murree beds northwestward from Rawalpindi, deposits of coarse boulders apparently belonging to this formation are locally found tilted to the vertical. It remains to be demonstrated whether or not this Pleistocene formation should or should not be included with the Siwalik as a final stage of that series.

LITHOLOGY OF THE NIMADRIC SYSTEM

SANDSTONE AND SILTSTONE

Throughout this system the beds are of a type which one associates with subaerial deposition. The main constituents are friable and frequently cross-bedded sandstones composed of fine to medium-sized grains, and alternating with these, or grading vertically and laterally into them, more dense beds composed of a mixture of gritty and clayey silt. Neither of the conventional terms, clay or shale, conveys a true picture of the latter beds. These have features of both clay and shale, and yet their dominant type is distinct from either. Although the finer phases and occasional lenses approach true clay, most of the deposit differs from clay in characteristically containing minute gritty grains, usually making up a major proportion of the volume, and in being in part indurated. It differs from shale in having a massive character which is wholly predominant over the occasional lamination. The term "siltstone," describing its correlative nature with sandstone, is more appropriate and will here be used.

The bulk of the siltstone is found, on washing, to consist of a fine powder of quartz grains mixed with grains or dust of many other materials, variously colored by iron staining. There are all gradations of texture from siltstone to the sandstone. The typical material of the latter is a gray sand composed of angular to subangular and poorly sorted grains of quartz, feldspar, mica, and many other materials of varied colors, commonly with a fine-grained matrix. This ensemble, having a kaleidoscopic appearance under the lens, is characteristic of the system. The greater portion of the sand grains range from a minute fraction up to one-half millimeter in diameter, the grains of diverse size and material being indiscriminately mingled. It is comparatively rare to find sandstones with grains, except those of mica, ranging to over two millimeters in diameter, and even in these the coarser grains are in a minority.

The siltstone beds do not, for the most part, have the hardness ordinarily connoted by the word stone. They are apt to be tough rather than hard. In part they are little more than dry compacted silt, but again they are cemented and hard, and there are all gradations of induration between. Much the same may be said of the sandstone, which locally is soft, although in general it is semi-indurated. The fine-grained sandstones show a tendency to be more indurated than the coarser. The hardness of individual beds, both of the sandstone and the siltstone, varies greatly from place to place, and a characteristic feature is the occurrence of pronounced induration in irregular ledges, lenses, and nodules in the midst of friable or even incoherent material. Embedded in the siltstone are often found nodules, comparable in shape with small potatoes, and smaller pellets, composed of the same material as the matrix but harder, due to a concentration of calcium carbonate. The latter is present in practically all of the beds and in some acts as a tight cement. Iron salts are also abundant, acting as cementing agents as well as coloring the sediments. Generally speaking, the average hardness of the beds increases the older they are in the Nimadric sequence. Much of the sandstone of the lower (that is, Murree) portion of the system is so indurated as to make a good building stone.

The varied coloration of the strata and the alternation of the deeper-toned beds of fine grain with the generally lighter-colored sandstone layers lends a gay aspect to the outcrops, especially in this semiarid region, where the structure is displayed in picturesque relief. A fact worthy of mention is that sandstone beds often partake of the deeper coloration of the siltstones close to their contact with the latter. It is interesting to note that the intensity of coloration gradually decreases upward in the Nimadric system, from the purplish and maroon shades of the lower portion to the prevailing whitish gray and straw and faintly reddish tones of the uppermost division.

The stratification afforded by the alternating massive sandstone and siltstone beds is conspicuous, and one is usually able to trace for long distances the clear-cut demarcation between the sandstone layers, which weather into prominence owing to superior resistance, and the more deeply colored and indented siltstone beds. It is also common, however, to find one type changing vertically or laterally, sometimes quite abruptly, into the other, and one can not rely on any individual bed continuing unchanged in thickness and character beyond the range of vision. Nevertheless, some of the beds are remarkably persistent and traceable for over a score of miles. Throughout the system cross-bedding is a notable and characteristic feature of the sandstone, and to a lesser extent it may be observed in the siltstone as well. For the most part the beds may be considered as lenses varying from a few feet up to a few miles in lateral extent.

The thickness of different beds varies from a fraction of an inch up to over 100 feet, and occasionally massive bodies of sandstone attain a thickness of two or three hundred feet, but the general rule is for an alternation from sandstone to siltstone, or *vice versa,* to take place every few feet. In addition to the bedding planes, stratification lines are often in evidence through the irregular hardening of layers. Indications of cut and fill along old minor stream channels are not infrequent.

A feature commonly noted is the depositional inclusion of irregular pockets, plates, or lumps of silt or clay in the sandstone, frequently oblique to the bedding, and the siltstone beds themselves locally contain pebble-like inclusions of similar material. These features present a partial gradation into the type of deposit next to be described.

INTRAFORMATIONAL CONGLOMERATE

Beside the sandstone and siltstone, a very characteristic deposit termed "pseudo-conglomerate" occurs in beds and irregular cross-bedded lenses scattered throughout the system. To convey an idea of the relative abundance of this sedimentary type, it may be estimated very roughly that something on the order of 7 per cent of the system has a "pseudo-conglomeratic" character. The deposit is most commonly composed of a sandy matrix containing lenses of siltstone, and full of a variety of small, pebble-like inclusions of siltstone and less often sandstone, of the same types as those forming the system itself and with little doubt derived from it. These intraformational inclusions show a wide range, from pebbles and subangular rock pieces that almost certainly have been rolled to angular fragments, usually of a flattish shape, which appear to have been already consolidated prior to being deposited in the matrix; to pellets and nodules that suggest concretionary character, and to irregular lenses as well as inclusions of a fragmental shape that appear to be depositional. The inclusions are apt to be more indurated than the material of the system as a whole and are often limy and ferruginous. They are also apt to display more pronounced coloration than the matrix, commonly showing purplish, reddish brown, and yellowish colors. The matrix itself is usually indurated with calcareous cement. In addition to the inclusions above mentioned, there are in some of these deposits scattered grains and pebbles of foreign rocks of a size larger than common in the adjacent beds. One common phase of the pseudo-conglomerate is composed of calcareous sandstone or siltstone full of hard pellets about 2 to 5 millimeters in mean dimension. These pellets are of gray to yellowish and reddish brown limestone or calcareous siltstone and ochreous material. The lenses of pseudo-conglomerate range up to many feet in thickness and at least hundreds of feet in length and they commonly contain vertebrate bones and teeth.

This strange type of deposit presents numerous interesting problems deserving special investigation and discussion. The writer believes that it represents frequently recurring times and places in which beds in the system were subjected to fairly prolonged exposure, to surface concentration of cementing agencies, and to drying and cracking, with the resultant reworking, transportation, and redeposition by wind and running water. Exposure of parts of the systems was very likely due both to local contemporary deformation and to local interruptions in the process of aggradation.

TRUE CONGLOMERATE

A feature of great interest in the Nimadric as displayed in this region is the relative scarcity of true conglomerate or even coarse-grained sandstone. Such deposits are abundant in the Upper Siwalik, but between that and the basal conglomerate of the system deposits of grits or pebbles derived from foreign rocks are present only in small proportion, scattered at wide intervals through the many thousands of feet of medium- and fine-grained beds, and accumulations of boulders or rubble such as one associates with subaerial piedmont deposits are absent. Lenses and stringers of water-born pebbles of crystalline rocks, of Nummulitic limestone, and various other rock types occur at several horizons in the upper part of the Middle Siwalik and in the Lower Siwalik (both Kamlial and Chinji) beds, but such deposits are small in comparison to the bulk of the fine-grained beds. This, taken with other features of the system, indicates that the beds were in the main spread out over level-lying plains, many miles from the hills or mountains that yielded their materials. Dr. B. R. MacKay discovered in the Middle and Upper Siwalik gravelly lenses cobbles that had planed surfaces and angular forms evidencing glacial abrasion. These may indicate that the region from which they were derived was one of high glacier-bearing mountains, comparable with the Himalayan range of today; or, as appears likely, they may have been derived from the boulder beds of the glacial Permo-Carboniferous series, which outcrops extensively in the Salt Range and Himalaya.

The upper few thousand feet of the system (the Upper Siwalik) are characterized by abundant gravelly zones and lenses ranging in coarseness up to boulder beds with boulders as much as a foot in diameter. In these occur abundant cobbles or fragments of limestone derived from the Nummulitic series, in addition to a great variety of other rocks.

DIVISIONS OF THE NIMADRIC SYSTEM

GENERAL STATEMENT

The following is a brief summary of the main subdivisions of the system, commencing with the oldest and omitting reference to common features already discussed. The separation into two main series, Murree and Siwalik, is followed for convenience and in order to conform with usage. It is to be noted, however, that the horizon at which a division is to be made between these two is indefinite and a real separation of the system into two series remains to be substantiated by stratigraphic evidence. Paleontologists report a great faunal break between the two, but the fauna known from the Murree is from its basal portion, and there are thousands of feet of intermediate beds for which faunas are not yet known. Probably a better classification can eventually be made by taking the whole system as a unit and dividing it into stages. There is no certainty that a dividing line can be found between Murree and Siwalik of more significance than the lines or, rather, gradational zones of change between various stages. The line now assumed as the top of the Murree and base of the Siwalik is, if anything, less significant than the one, for instance, between the Kamlial and overlying Chinji stages, presently to be mentioned. If a real break in sequence occurs between Murree and Siwalik, it should probably be looked for considerably lower down than the line now assumed.

MURREE SERIES

The basal portion of the Nimadric system, where observed in the belt along the foothills of the Himalaya, consists of a variable zone about 200 feet thick, composed largely of brown, ochreous sandstone with subordinate beds of siltstone and "pseudo-conglomerate." Locally, and especially at the very base, it contains abundant nummulitic and occasional other fossil shells, evidently derived from the Eocene beds, and also contains pebbles, cobbles, and fragments of Nummulitic limestone and other rocks. Locally a conglomerate of shale flakes of the "pseudo-conglomerate" type lies directly on the Eocene and assumes the rôle of a basal conglomerate.

Succeeding this basal zone come thousands of feet of strata, consisting mainly of massive maroon and purplish brown sandstone interbedded with thinner beds of purplish siltstone. The sandstone beds are resistant and form prominently outstanding ledges and escarpments. Occasional sandstone beds are soft and are of a light bluish green, brown, or other color. Sandstone forms the bulk of this division.

In the upper part of the sequence called Murree, in apparently gradational relationship with the beds both below and above, comes a softer and more predominantly silty stage, at least some hundreds of feet thick, composed of gray, reddish, and purplish siltstone interbedded with gray and greenish gray sandstone.

The Murree beds, with locally infolded members of the Nummulitic series, form a continuous belt from 12 to 16 miles wide, fringing the northern side of the Potwar and separating the areas of Nummulitic and older rocks on the north from the Siwalik-covered region to the south. This belt being one of severe compression, the Murree beds doubtless owe much of their induration to the deformation undergone here. Beds ascribed to the upper part of the Murree come to the surface in a few isolated structures farther south and have a much less indurated character. It is probable that the difference in hardness between typical Murree and typical Siwalik, which forms one basis for their separation into series, is due more to the difference of geographic and structural position of their area of outcrop than to any great break between them.

The total thickness of the Murree series is difficult to make out, owing to the close folding and severe faulting that it has undergone in the piedmont belt where it is best exposed. Subsequent work affords no basis for altering Wynne's early estimate of 5,000 to 8,000 feet. As already mentioned, the series thins southward and lenses out entirely in places on the north flank of the Salt Range uplift.

With reference to the nummulites in the base of the Murree, it is clear that these fossils come from the beds of the Nummulitic series and represent a process of weathering and reworking of the material of the basement on which the Murree deposits gathered. It is characteristic of the Nummulitic beds of India and elsewhere, especially in dry regions and in the case of the marly and "nummulite shale" facies, to yield a rubble of almost perfect nummulite disks which become distributed through the adjacent alluvium and, owing to their wafer or buttonlike shape, are readily transported, both by water and wind, for considerable distances without much wear.

The combined evidence clearly establishes an erosional unconformity between the Nummulitic and the Murree, although it does not appear that within the immediate region under discussion the uplift of the former coincident with the withdrawal of the sea brought about severe deformation. The Nummulitic strata are actually truncated in places by the overlying series, and the latter lies on different horizons of the former at different places, but the angle of discordance in dip is slight and in general not readily noticeable.

SIWALIK SERIES

General statement.—Set off somewhat arbitrarily from the lower portion of the Nimadric system, as above described, the Siwalik is itself conveniently divisible into several lithologic stages. These divisions, viewed as a whole, have distinctions sufficiently constant to enable them to be traced throughout the northwestern Punjab and, at least in this region, represent periods of slightly varied conditions of sedimentation; but they are hardly to be considered as distinctly separable stratigraphic units. Each stage appears to grade conformably into the next, and, owing to the transitional zone, 200 to 500 feet thick, that usually occurs between any two, as well as to lateral changes in lithology, the dividing lines are not precise nor always recognizable at exactly the same horizon. The main divisions are commonly described as the Lower, Middle, and Upper Siwalik, the former being divided into two characteristic portions, termed the Kamlial and Chinji. The outstanding features of these will be described, beginning with the lowest.

Kamlial stage.—In the Salt Range the Murree series is represented, if at all, by a much reduced thickness, and along at least part of the range is believed to be absent. In its place, lying with erosional unconformity and basal rubble upon the Eocene, are prominent sandstone strata which are assigned, on both stratigraphic and paleontologic grounds, to the Lower Siwalik. These strata, together with interbedded siltstones in lesser volume, make up a formation about a thousand feet thick which is widespread in the Potwar Plateau region. It was given the name Kamlial by Pinfold in the Khaur oil field and assumed as the lowest member of the Siwalik series. The typical Kamlial consists in the main of resistent, ridge-forming sandstone, the individual beds ranging in thickness up to over 100 feet. Sandstone composes on the average about four-fifths of the formation, the balance being intermediate and less prominent beds of siltstone, which range in thickness from a few inches up to 30 feet and occasionally more. The proportion of sandstone to siltstone is by no means constant, however. For instance, as one traces the formation eastward to and beyond the east end of the Salt Range, the proportion of silt greatly increases. Many of the sandstone beds are "pseudo-conglomeratic" or contain inclusions of that type in varying abundance. As disclosed in the Jhatla well, about 15 per cent of the Kamlial-Murree beds showed such inclusions. The sandstone is chiefly gray and greenish gray, though varying in color to reddish and purplish brown. The siltstone is mainly of maroon, purplish, reddish brown, and greenish shades. A noteworthy feature is that the purplish tinge in both sandstone and siltstone is more characteristic of the lower portion of the stage, giving it a strong resemblance to the Murree beds. Upward in the Kamlial the color tends to change to a lighter tinge, more like that of the Middle Siwalik.

No recognizable dividing line nor definite basis of division between the Murree and the Siwalik have been established, and it is not unlikely that in places the lower portion of the terrain that lends itself to mapping as Kamlial actually represents what is elsewhere called Murree, especially where the terrain is thick. Its thickness is 900 feet, as set off in the Khaur anticline from the underlying variegated siltstone beds, which Pinfold considered to be the representative of the Upper Murree. There is no sign of a stratigraphic break and the separation is made on the basis of lithology, the beds termed Kamlial being a ridge-forming body mainly of sandstone.

In the northern belt of outcrop of this stage, about 10 miles north of Khaur (Chirpar Hills) and extending westward toward the Indus (near Gulial, etcetera) and northeastward to south of Rawalpindi and beyond, a total distance of over 85 miles, the thickness of beds that might be correlated as a whole with the Kamlial on lithologic grounds ranges between 1,000 and 2,000 feet. This may include beds at the base equivalent to those called Murree at Khaur, but part at least of the increase is believed to represent northward thickening of the stage. The other main belt of outcrop forms the southern border of the Siwalik area, running in a general east-west direction for over 120 miles along the Salt Range and its appendages. There the formation has a thickness ranging from about 900 feet upward. Much of the thickening takes place at the base of the terrain and probably represents beds called Murree in the north. The varying thicknesses of this Kamlial-Murree terrain in the southern belt are approximately as follows: 1,400 feet near the Indus; 1,000 feet near the sharp bend and highest portion of the Salt Range, 30 miles southeast of the Indus, gradually increasing thence eastward to 1,300 feet in the central portion of the range, to 1,550 feet near Kallar Kahar (not including the prominent transition zone of beds at the top, about 500 feet thick, which has been arbitrarily included with the overlying Chinji), and to 2,070 feet on Diljabba Ridge, 25 miles east-northeast from Kallar Kahar. Twelve to 17 miles farther northeastward, on the Bakrala anticlinal ridge, the Kamlial-Murree terrain has a thickness of about 2,000 feet, and here its lowest beds, which are presumably pre-Kamlial in age, contain abundant vertebrate bones. A similar thickness (2,011 feet) was found in the Jhatla well, 10 miles north of the central portion of the Salt Range. On Mount Tilla, 20 miles southwest of the town of Jhelum and 12 miles southward from the Diljabba and Bakrala

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sections, the thickness is 1,800 feet; but just to the south of this, on Chambal Ridge, which intervenes within the few miles that separate Mount Tilla from the plains of the Jhelum River, the thickness is only 900 to 1,000 feet.

Most of the northward thickening that is indicated by these figures for the Salt Range region is presumed to indicate the entrance at the base of the section of beds equivalent to those called Murree farther north. On the Bakrala anticline an attempt to make a separation shows a thickness of 1,100 feet that may plausibly be assigned to the so-called Murree on the ground of its purplish color and the predominance of siltstone, and an overlying formation about 900 feet thick of more reddish sandstone and siltstone ascribable to the Kamlial.

Chinji stage.—Toward the top of the Kamlial the proportion of siltstone increases and there succeeds a finer-grained formation ranging in thickness from 1,400 feet in the southern region to about 4,500 feet in the northern. Taken as a whole, this body of beds has a distinctive character, making it the most readily recognizable of all the stages of the system. It was named by Pilgrim the "Chinji" from a village at the edge of the belt of low relief which these beds form for over a hundred miles along the northern foot of the Salt Range. The same formation is equally extensive in outcrop through the northern portion of the Potwar Plateau. It is composed mainly of siltstone having a warm orange-brown color, regularly banded with lesser beds of ash-gray sandstone. The banding produced by these contrasting colors gives a picturesque effect to the landscape. Of this deposit as a whole the siltstone composes on the average about 70 per cent in the southern belt and a lesser, though still predominant, proportion in the northern one. The siltstone beds vary in thickness up to 200 feet or more, although generally only a small part of that. The sandstone layers rarely obtain a fifty-foot thickness and are usually measurable in terms of only a few feet. The color of the siltstone varies in depth of orange shade, and also to yellowish, brownish, brick red, and purplish hues, whereas the sandstone often assumes an olive and occasionally a purplish color. Lenses of "pseudo-conglomerate" are scattered through the Chinji and occur particularly in its basal portion, but are generally thinner and less abundant than in the more dominantly sandy parts of the system.

The Chinji gives unmistakable evidence of thinning progressively southward. In the northern belt of outcrop, parallel to that described for the Kamlial, its thickness ranges between 4,000 and 4,500 feet. A few miles south of this belt, on the south flank of the Khaur dome, its thickness is approximately 3,500 feet. As revealed in the Jhatla well, 30 miles farther southward, it is 2,800 feet, and 8 miles southward of this, in the type section at the north foot of the Salt Range, the thickness is 2,400 feet. Following the outcrop westward along the latter belt, the Chinji thins to about 1,500 feet near the Indus end of the Range. Eastward from the type section it maintains a fairly even thickness for some miles, but then thins to 2,100 feet on Bakrala Ridge, 60 to 70 miles northeastward from Chinji village. A dozen miles southward from Bakrala Ridge it ranges between 1,550 and 1,900 feet on Mount Tilla, and farther southward attains apparently only 1,370 feet on Chambal Ridge, although at the latter place the thickness may be considerably more, depending on where one draws the upper line.

Middle Siwalik.—The Chinji is fairly sharply overlain by massive gray and grayish buff sandstone, some beds of which have a thickness of 200 to 300 feet. Such sandstone, alternating with usually thinner beds of brownish, tile-red, buff, and yellowish siltstone, continues several thousand feet upward in beds and zones of varying thickness to form the middle division of the Siwalik. In the regions of its best development this division attains a thickness of five to six thousand feet, but it is subject to great lateral variation, both in lithology and thickness. Masses of "pseudo-conglomerate" are characteristic. Sandstone forms the great bulk of this division in the western portion of the Potwar Plateau, but northeastward the siltstone members take the place of much of the sandstone and toward Rawalpindi make up about half of the total volume. Concurrently the siltstone beds, as they increase in thickness, assume a deeper tone of reddish brown. A similar reduction of the sandy phase and increase of the volume of silts is noted to the southward, but as a whole the group is characterized by its thick sandstone zones. Gray is the dominant color of the sandstone, but this varies from light to dark gray, and to greenish and brown shades.

Owing to the lithologic variation and the difficulty of recognizing a consistent line of separation between the Middle and Upper Siwalik, it is impossible to give reliable figures as to the comparative thicknesses of these divisions in different areas. For instance, in the north central portion of the Potwar the Middle Siwalik comprises mainly sandstone from 5,000 feet thick (Dhulian anticline, between Pindi Cheb and Soan River) to 6,000 feet (Ahmdal syncline, north of Khaur), whereas a decided thinning of this sandstone mass takes place both to the west and east and also to the south. Forty miles westward from Khaur, on the north flank of the faulted Dakhnir anticline near the Indus, the thickness of the beds, which were mapped as Middle Siwalik, is about 3,500 feet, and a similar distance eastward from Khaur the thickness is not much over 2,000 feet; but with this thinning there appears to go a thickening of beds resembling the Upper Siwalik. In the southern portion of the Potwar—that is, south of the Soan synclinal basin—the Middle Siwalik is represented by from 2,000 to 3,000 feet of predominantly sandstone beds overlain by thicknesses varying up to as much again of mingled siltstone and sandstone which might be ascribed to either Middle or Upper Siwalik.

Upper Siwalik.—The Upper Siwalik is distinguished by the very greatly increased volume of conglomerate and coarse sand, as compared with the older parts of the system. Locally a line of separation between the Middle and Upper Siwalik divisions can be based on the entrance of thick deposits of conglomerate, representing the commencement of a more torrential type of deposition. Elsewhere, however, there is perfect gradation. Conglomerates also occur in the Middle Siwalik and suggest that the transformation in the conditions of sedimentation was a progressive and not a sudden one. The Upper Siwalik, as a whole, is the most variable division of the Nimadric system. It is not unusual to find thick zones of siltstone or sandstone which locally might be taken to have almost formational importance changing laterally into coarse conglomerate, or *vice versa.*

Aside from the conglomerate, which forms a considerable, though still subordinate, part of this division, the Upper Siwalik is composed largely of whitish gray and brownish sandstone and semiconsolidated sand and siltstone beds of varying shades. Among these shades are straw and mustard colors, faint lavender, greenish gray, buff, orange, and even deep tile red. On the whole, however, this division is lighter-colored than lower parts of the system and less bright and variegated than the enumeration of these colors might suggest. Some individual conglomerate lenses are as much as 250 feet thick. The inclusions are well water-worn pebbles, cobbles, and boulders of metamorphic, igneous, and other rocks, including Nummulitic limestone. The boulders do not usually exceed a diameter of 10 inches. The Upper Siwalik forms the surface of approximately half the Potwar Plateau, occupying the synclinal basins and being absent, almost certainly owing to erosional removal, on the summits of all the anticlinal domes.

The thickness gradations of the Upper Siwalik are difficult to estimate, owing to its higher portions being locally worn away or hidden and owing also to its changing facies and the doubtful correlation from region to region of the line of separation from the Middle Siwalik.

The beds mapped as Upper Siwalik have the following approximate thicknesses in various districts: Near the Indus, in the northwestern part of the Potwar, 5,500 feet; in the center of the Soan syncline, in the western part of the Potwar, 4,500 feet (but probably not all present); in the Soan syncline, south of Khairi Murat Ridge (southwest of Rawalpindi), over 6,000 feet (but probably including some Middle Siwalik); and in the Jhelum district, to the southeast, 1,500 to over 4,000 feet, depending on where the base is placed. A more correct idea is conveyed by combined thicknesses of Middle and Upper Siwalik beds exposed in single sections, some of which are roughly as follows: Northwestern part of the Potwar (Dakhnir anticline), 9,000 feet; northeastern part of the Potwar (south of Khairi Murat Ridge), 8,500 feet; Bhaun syncline, in south central part of the Potwar, 4,650 feet, with only 1,500 feet (probably lower part) of Upper Siwalik present; region of Bakrala Ridge, about 25 miles northwest of Jhelum, 8,000 feet; region of Chambal Ridge and Kharian anticline, south of Jhelum and at edge of the plains, 5,500 feet.

STRUCTURE

GENERAL STATEMENT

The Potwar Plateau is, broadly speaking, a geosyncline between the Salt Range on the south and the front ridges of the Himalaya on the north. By the latter ridges are meant the mountain outliers and hills which form a southwardly convex arc extending from Muzaffarabad, on the Jhelum, and from the hill station of Murree southwestwardly to the Indus some miles downstream from Attock. This arc and the similar ones farther north are included with the Himalaya Range, although, as pointed out by several writers, their trend allies them to the Hindu Kush Range and sets them off from the southeastward-trending structures of the main Himalayan arc east of the Jhelum.

The structural axes in the Potwar region run generally parallel with the ranges to the north, usually along east-northeast and west-southwest lines. The parallelism of the Salt Range with the northern arcs is striking, but as would be expected in a wedgelike segment such as this region is, between the northwest-southeast arc of the Himalaya east of the Jhelum and the north-south lineaments of the Suleiman ranges west of the Indus, the structures here, and particularly at the ends of the Salt Range, show the effect of compression from the sides. These various features are displayed in the topography, and the recency of deformational movements is reflected in anticlinal and fault ridges and synclinal basins.

Along the northern belt the strata are highly compressed and faulted, the dominant feature of the structure being overfolding and overthrusting from the north. The belt contains in closely packed space a concentration of broken segments resulting from foreshortening. The series there are Murree, Nummulitic, and older. Southward the structures become more simple and moderate, so that the central and southern portions of the Potwar Plateau, as well as the Salt Range, contain wide areas of gentle dip and several broad folds. The Siwalik beds cover the major portion of the central and southern area. The southeastern portion of the region, within a radius of 30 miles or so of Jhelum, is an exception to the comparatively gentle structure just mentioned. This district contains several compressed and southward thrust anticlines that form ridges extending northeastward from the Salt Range. The latter range itself is a northward-dipping monocline or the north flank of an original broad anticline which has been overthrust to the southward. Evidence of the overthrusting is mentioned in the discussion of the Eocene system early in this paper. The overthrust mass, and particularly its southern face, has broken down in numerous places by normal faulting, such collapse being doubtless aided by solution in the salt and gypsum beds that form the basement. The scarps facing the plains to the south expose above the Eocene "salt marls" a two to three thousand foot section of moderately tilted strata ranging upward from early Paleozoic to Eocene. On the other hand, the crest and northern side of the range is formed mainly by the Nummulitic limestone and Lower Siwalik sandstones, which dip northward beneath the Potwar geosyncline.

It is to be noted that the area now occupied by the Potwar and regions of unknown extent to the north within the present Himalayan province (as well as to the south during the Siwalik epoch) formed part of the submontane depression in which the Nimadric system was accumulated. The present geosyncline of the Potwar Plateau represents only a foreshortened portion of the original plains.

The depth of the top of the Nummulitic in the deepest parts of the present geosyncline is seventeen to twenty thousand feet below sealevel, on a conservative estimate of the thicknesses involved, and nearly 2,000 feet more below the present level of the country. Thus, if we consider the rim of the basin as being at the general level of the lower outcrops of the Nummulitic on the sides, we get a figure on the order of 20,000 feet or more as the present depth of the saucer filled by the Nimadric system. Actually the Murree beds rise to over 7,000 feet in the Himalayan front range near Murree, and the Nummulitic limestone forms heights still more elevated. These figures convey an idea of the scale on which dislocation of the crust has gone on and the scale of deformation represented by the vast thickness of Nimadric deposits.

STRUCTURAL ZONES

Dr. MacKay's summary.—Dr. B. R. MacKay, in a report submitted in 1922, gives the following summary of the structural features of the region, partly following Pinfold's description:

Based on the prevailing types of structures present, the region may be divided into a number of structural zones. From north to south, these are: (1) the isoclinal zone, (2) the fault zone, (3) the anticlinal zone, (4) the Soan synclinorium, (5) the terrace zone, (6) the Salt Range monoclinal zone, and 7) the Salt Range anticlinorium.

The zones are exceptionally well developed in the central part of the region, between longitude 72'° 00″ and 72° 45′. Most of the region lying between the Soan synclinorium and the Jhelum River to the southeast may be considered as constituting a separate fault zone, whereas the terrace zone of the western part of the district gradually merges eastward into a separate anticlinal zone.

Isoclinal zone.—In the northern part of the area, along the Margala and Kala Chitta ranges, the rocks are so intensely squeezed, crushed, faulted, and overturned that in many parts it is impossible to represent the structure correctly on a map of a scale of 1 inch to 1 mile. This belt of greatly disturbed strata extends from the Jhelum to the Indus River and has a width of about 20 miles. It is bounded on the south by a marked strike thrust-fault, which crosses the Indus near Jand and which is traceable eastward from the Indus for a distance of over 40 miles, passing to the south of the Khairi Murat Range. Over most of this area the folds are not only overturned southward, but are so tightly squeezed that nothing remains of their crests, and both limbs lie in contact, so that they can be distinguished only by the most careful scrutiny.

Fault zones.—To the south of this fault the folds are much more open and the rock succession is easily elucidated. For a distance of 12 miles immediately south of the fault, in the vicinity of the Indus River, the rocks are arranged into a series of open synclines separated either by strike-faults or closely folded anticlines. On most of these synclines the axial planes dip to the north. The synclines are closely packed together and generally separated from one another by narrow saddles. At least four prominent strike-faults occur within this zone, all of which dip to the north. This fault zone is limited on the south by a prominent fault which crosses the Indus near Malangi, 16 miles south of Khushalgarh, and extends eastward for a distance of over 15 miles. This fault lies along the crest of the Dakhnir anticline and apparently plays out on the south flank of the Kharpa fold.

Between the Soan River and Jhelum occurs a zone, over 40 miles in width, characterized by a series of broad, open synclines, separated from one another by long, narrow, tightly squeezed and in places overturned anticlinal structures. Strike-faulting is generally pronounced along the axis of the anticlines, and the shortening that has taken place is indicated by the lost intervals which occur on the northern flanks of the synclines and the southern limbs of the anticlines.

Anticlinal zones.—Lying south of the Malangi boundary fault, there occurs a belt, about 12 miles in width, extending from the seventy-second meridian eastward to meridian 72° 45′, which is characterized by a large anticlinal fold with the Dhulian and Khaur domes as the crestal areas. This zone has been aptly termed by Pinfold the "anticlinal zone."

Another section of the district characterized by the development of prominent anticlinal structures stretches north-eastward from the eastern end of the Jhatla dome for a distance of about 40 miles, where it passes into the fault zone of the eastern district. In the vicinity of the Jhatla dome this zone has a width of about 8 miles, and gradually increases eastward until it attains a width of over 12 miles.

Soan synclinorium.—The central zone of the Rawalpindi (or Potwar) Plateau is characterized by a broad synclinorium, which extends from Murree southwestward and westward to beyond the Indus River. In the central part of the district the synclinorium has a width of about 15 miles, while near the Indus the width increases to approximately 25 miles. The shallowest part of the synclinorium lies between the Dhulian and the Jhatla domes, while to the northeast and to the west of this there occur conspicuous basins, 2,500 to 3,000 feet deeper. The axis of the synclinorium parallels and lies a little south of the Soan River, from which stream it derives its name.

Terrace zone.—In the central and western part of the district the southern flank of the Soan syncline rises gently and flattens off to form a broad terrace belt which extends from the Indus River eastward to beyond the Jhatla dome. This terrace is especially well developed in the region northeast of the Jaba seepages and in the vicinity of the Jhatla dome.

Salt Range monocline.—The Salt Range monocline constitutes a belt 4 to 10 miles in width of northeastward and northward dipping strata along the northern flank of the Salt Range. The dips of the strata over this zone vary from 5 to 60 degrees, exposing in certain sections a thickness of over 4,000 feet of Siwalik sediments. To the east of the Jhatla dome the monocline is not so well defined as in the western Salt Range, owing to the intense faulting and crushing which characterize this part of the district, but it may be considered as conforming with the northward slope of the main Salt Range eastward as far as Chambal Ridge.

Salt Range anticlinorium.—The Rawalpindi Plateau is terminated on the south by the Salt Range, a broad anticlinorium on which are developed a number of minor folds. The structure is characterized by very gentle dips on the northward slope and much steeper dips on the southern flank, where remnants of this flank remain. Throughout most of its length no evidence of the southern limb of the anticlinorium is to be found, and it is believed that this flank has been overridden by the northern flank, as a result of an overthrust from the north. From the Indus River eastward to beyond the seventy-third meridian the Salt Range forms a single anticlinal structure, but to the east of the seventy-third meridian it breaks up into three prominent spurs, the Bakrala anticline, the Mount Tilla anticline, and the Kharian anticline, with a number of subsidiary folds.

Range and Source of Petroleum

It is not within the scope of this paper to describe the numerous seepages and other evidences of petroleum, but they may be briefly summarized as occurring primarily in the Nummulitic series, and mainly, though not wholly, in its upper division, where their best manifestations as seepages are in fine-grained sandstone beds. Secondarily, they occur in such beds of the Nimadric system as lie in favorable structural positions on the Nummulitic. Locally the petroleum has risen through many hundreds of feet of the basal Nimadric beds, this being most markedly the case in the sharply anticlinal and moderately faulted Khaur oil field, where it has collected through more than 2,000 feet of these beds. No strata have been found in the Nimadric which could be considered a source for the oil, and the evidence all points to the highly foraminiferal and otherwise fossiliferous deposits of the Eocene as the original source.

Tertiary History

GENERAL STATEMENT

An attempt will here be made to interpret briefly what must have been the conditions during the post-Eocene period, in view of the character, distribution, and structure of the Tertiary strata in this portion of India.

CONDITIONS REPRESENTED BY THE NIMADRIC SYSTEM

Subaerial deposition.—The greater part of the Nimadric strata were, with little doubt, accumulated subaerially through the agency of streams, aided by the wind. The deposits are of a fluviatile type, with the admixture of much material that might be windborne. The fairly well stratified, although cross-bedded and lenticular beds, the relatively homogeneous zones traceable over wide stretches of country, and the fine-grained silty and sandy nature of most of the system represent sedimentation on broad plains, over which rivers of considerable size and low gradient meandered. There probably were local and temporary lake and marsh accumulations, though such have not been definitely recognized in the strata themselves. The remains of diving birds of the pelican group bear testimony to the presence at times of considerable bodies of water. The bones of such animals as crocodile, hippopotamus, turtle, etcetera, suggest floodplain streams, in harmony with the evidence of the sediments.

Balanced uplift and subsidence.—The vast thickness of the system and its relative similarity throughout leave no room for doubt that there was a long-continued process of gradual subsidence of the basin in which it was laid down—a subsidence that kept approximate pace with the rate at which sediments were supplied and were spread over the plains. Until the close of the Middle Siwalik, the highlands which furnished these sediments must have been at a considerable distance from the area which received the deposits now preserved. The coarser submontane phases which doubtless existed originally must have been far within the district now occupied by the mountains, where they have been worn away. Temporary or local interruptions, or even reversals of the process, may have taken place, and it is fairly certain from the changing facies of different parts of the system, as previously described, that at least the rate of the processes was variable. Presumably, for instance, the dominantly sandy formations in the Murree, Kamlial, Middle Siwalik, and, above all, the conglomerates of the Upper Siwalik denote rejuvenation of the mountains and streams; but, viewed in the large, the system is the record of a continuing major process of concurrent subsidence and aggradation of the plains, combined with uplift and erosion of the tributary mountain areas. These activities served to balance each other in a remarkable way, so as to preserve the equilibrium of a fairly constant surface elevation and conformation of the plains and a constant source of sedimentary material. The system affords a magnificent demonstration of the coordination of these joint processes.

Similar sedimentation today.—The conditions of sedimentation may be fairly closely pictured by comparison with those prevailing today over the plain of the Ganges and the Indus, which, judging by its low elevation above the sea and the thickness in places of its alluvial fill, is in part undergoing subsidence and aggradation in continuance of the processes prevailing earlier. The relation and position of mountains, plains, and sea during the Nimadric period were probably very similar to those of the present, except that in the earlier part of the period arms of the sea approached on the southwest nearer than today and penetrated deeply the present continental area in the Assam region on the east.

Climate.—Climatically, also, the conditions were presumably comparable with those of the present, with seasonal winds from the ocean on the south bringing moisture and precipitating it on the plains and on the southward-facing slopes of the encircling mountains; but the climate in the Punjab region would appear to have been less arid than now and more similar to that of portions of India somewhat farther east. The remains found throughout the Siwalik series of an extraordinarily rich and varied fauna of herbivorous animals bear witness to the existence during that epoch of vegetation and moisture in excess of that of the Punjab today. They also help to confirm the picture, deduced from the sediments themselves, of wide-spreading floodplains on which these animals found pasture.

Pieces of tree trunks, lignite laminæ, and poorly preserved palm and other plant remains scattered through the system are in accord with this conclusion, although leaves and stems are not as abundant as might, perhaps, be expected. The occurrence in the Siwalik of petrified logs, and also the bones of primates, which presumably were arboreal forms, show that the region was at least locally wooded. The scarcity of soluble salts in the beds, as indicated, for instance, by the freshness of the underground waters obtained in the deep Jhatla well, is a further evidence that the region was not arid.

On the other hand, there is support for the belief that the climate was intermediate between the semiarid condition now prevailing in western India and the tropical jungle type of eastern India. The preservation of the bones in such abundance suggests a certain degree of dryness, especially as many of them show the effect of long exposure to weathering before being buried. The "pseudo-conglomerate" deposits and the absence, so far as the writer has observed, of old soil deposits also convey a similar impression. The reddish colors characteristic of many of the strata throughout the system, and present at depth in wells just as in surface exposures, probably indicate that such beds were subject to seasonal or occasional drying; and the presence of animals ancestral to the modern giraffe, camel, and ostrich appears in harmony with the idea of moderate precipitation. The mingling of these animals with the numerous species of elephants, with horses, oxen, antelopes, rhinoceros, lizards, and other forms, including their carnivorous associates, bears out the conception of a locally forested and locally open country of low relief, under a semitropical climate of medium rainfall. Judging from the profusion and variety of the fauna and its continuity of development through long periods, the life conditions must have been unusually favorable, as well as comparatively stable.

These deductions as to climate apply mainly to the Siwalik portion of the period, inasmuch as beds definitely known to be Murree have not yet yielded good remains of a fauna except from the lowermost zone. In such a long period it would be rash to imply that changes did not take place; but the above conditions are those indicated to have been predominant, and such data as we have from the Murree beds (palm and other plant remains, similarity of sediments to those of the Siwalik, vertebrate fauna in the basal zone and in other beds believed to be Murree) support a presumption in favor of similar conditions during the Murree epoch. It is to be noted that the moderately rainy climate of the Nimadric period contrasts with the aridity which must have prevailed in the epoch represented by the saline deposits of the Nummulitic. The formation of the ancestral Himalayan Range was probably the chief factor in this transformation, providing a barrier in the path of moist winds from the south.

Orogenic sequence.—At the close of the marine period of the Eocene there was uplift of continental proportions which elevated a vast area above sealevel. This was evidently not merely linear deformation, creating one or more mountain ranges, but rather a fairly uniform uplifting of the former marine basin to above sealevel without strong deformation in the region here discussed. Coincident with or following on this movement, however, there were presumably reawakened deep-seated zones of shear which became projected to the surface in the form of flexures in the blanket of Eocene deposits, thus creating local highlands. Such a mountain area must have been within the present Himalayan province, but far to the northward of the front ridges of today. An ancestral Salt Range was also one of these uplands, as shown by the almost complete removal of the upper stage of the Nummulitic from the top limb of the range, by the entire or approximate absence there of the Murree series, and by the coarse fragments of Nummulitic limestone inclosed in the basal beds of the continental system as laid down there. In the Salt Range area the great Paleozoic and Mesozoic succession of strata had been previously little disturbed, but there is evidence in old unconformities that the post-Eocene flexing took place along an ancient zone of warping.

With uplift of the Nummulitic series erosion affected particularly the more elevated tracts just mentioned, thus bringing about during an epoch intervening between that of the Nummulitic and that of the oldest Nimadric beds so far recognized the eroded surface of gently uptilted Eocene and locally older strata on which the Nimadric of this region was deposited.

Judging by the mass and character of the Nimadric sediments, the grains of which resemble the Himalayan rock types, by the thinning of the members southward, and by evidence that deformation and erosion both prior and subsequent to the Eocene has progressed much farther in the mountain province than elsewhere in this general region, it may be assumed with assurance that the ancestral Himalayan Range was the chief source of the materials. The continuing process which gave rise to these deposits is inferred to be as outlined in the following paragraphs.

Uplift in the Himalayan province constantly progressed by means of compressional forces first folding and then upthrusting the strata of that range. Such thrusting in this immediate region was southward or south-southeastward along numerous more or less east-west lines. As the rocks of the mountains, including the Eocene strata, were pushed upward and southward, the plains region to the south received the products of erosion and concurrently subsided. It would seem that such subsidence might readily be due in part to overweighting by the encroaching mountain mass as well as to the loading on it of sediments. Downwarping of the lower limbs of overturned frontal folds also doubtless played a part. The depression of the plains segment may best be interpreted as a downward tilting of the northern fringe of the land on the south with the greatest amount of subsidence near the foot of the Himalaya, as indicated by the declining thicknesses of the Nimadric deposits southward. For a time the general zone of the ancestral Salt Range would appear to have formed the southern boundary or hinge of the sinking area, because the evidence goes to show that it was the southern limit of deposition of the Murree beds. Later, the Salt Range area subsided with the rest and was buried beneath several thousand feet of the Siwalik sediments. During this later period the southern edge of the depressed area was much farther to the south, as indicated by the normal succession of Siwalik deposits in the Salt Range monocline and around the eastern end of the range. The possibility suggests itself that the northward-dipping ancient strata reported seventy-five years ago by Fleming in the isolated Korana Hills, which rise out of the plains some fifty miles south of the Salt Range, represent deformation, perhaps southward thrusting, along the southern hinge of this Siwalik downtilting or downwarping.

As the processes above mentioned progressed it is to be inferred that a southward transgression or growth of the Himalayan Mountain area took place by means of forward movement on many thrust-planes, and as a result of new folds and thrusts that developed in the belt of previously little-disturbed Eocene, and in the Nimadric beds themselves, along the southern border of the mountains. Evidence of this is afforded by the upper (Chharat) division of the Nummulitic and the Murree beds being involved in the severe overfolding of at least the front ridges of the Himalaya, although it remains to be proven that any of the disturbance of the Murree beds, in the structures where they are still preserved, was earlier than late Tertiary. The amount of foreshortening that the Eocene and Nimadric beds have undergone through close folding and overthrusting, as well as through the more open folding of the Potwar, shows that the original plains on which the subaerial system was laid down were far wider in a north-south direction than the present area of outcrop. Other evidence of such southward growth of the range is to be found in the absence along the northern border of the Potwar of the coarse submontane phases of the lower and middle portions of the Nimadric system, which must originally have occupied northward extensions of the basin of deposition. These evidences combined serve to set back to the extent of scores of miles the Himalayan front in the earlier ages of the Nimadric period, and similarly it is certain, from the evidence of overthrusting of the Salt Range, that the ancestor of the latter range was miles to the northward of its present position.

At about the beginning of the time represented by the Upper Siwalik, and the commencement of deposition of gravel and boulder beds, there came the most marked change of which we have record in the conditions of deposition of the system. There was either pronounced uplift of the tributary mountain areas and rejuvenation of the rivers or a forward thrusting of the mountains to bring them closer to the area of deposition. The evidence indicates a combination of these causes. To supply the coarse conglomerates which we find, the mountains must have been both high and close. Another factor which very likely had a part, but which could not have been sufficient alone to account for the coarse deposits of the Upper Siwalik, was increased seasonal precipitation, with the consequent increased transporting power of streams. It is to be noted that a somewhat greater concentration of rainfall in the immediate region represented by these deposits would be expected to result from the rise and nearer approach of the mountain front. Indication of such greater precipitation may perhaps be afforded by the decrease in density of coloration by oxidized iron compounds in most of the later Siwalik as compared to the earlier portions of the system.

The inference is drawn that the encroachment of the mountains was not a sudden thing, taking place toward the end of Middle Siwalik time, and again at the end of the whole period, but was a gradual process, going on, with minor interruptions and occasional stimulation, throughout the Nimadric period. Evidence in support of this is to be found in the continual supplying of great amounts of sediment, of fairly constant types, which indicates progressive rejuvenation of the mountains keeping pace with erosion. Southward overfolding and thrusting, being a dominant structural tendency in this region, undoubtedly was one, if not the major, factor in the process of rejuvenation. In addition, the indications of southward transgression of the deposits, without evidence of greater distance from the source of supplies, supports the view that the encroachment of the mountain province was progressive. The great sandy formations in the system presumably indicate the periods of prime activity, whereas the dominantly silty formations, like the Chinji in particular, may be taken to represent periods mainly of quiescence and wearing down of the mountains.

The period ended with deformation affecting the whole system and, for the time being at least, terminating the process of regional subsidence within the Nimadric province. The information so far obtained does not warrant a definite conclusion as to whether the folding and faulting of all the beds of the system in the region where they now outcrop was brought about by severe deformation concentrated at the end of the period or represent a culmination of activity commencing earlier. It is not yet known whether the latest beds of the system were laid down coextensively with those preceding or represent deposition in slightly restricted basins produced by warping. It is possible that the folding of parts of this province began contemporaneously with the activities already mentioned as being indicated by the Upper Siwalik type of sediments; but the Upper Siwalik participates in all the folds, both moderate and severe, being tilted parallel with the earlier strata, and it is clear that most of the folding and faulting of the Potwar and Salt Range region was brought about after the close of the Nimadric period. We must look to the present mountain region farther north for the main locus of deformation indicated as having taken place during earlier portions of the period.

In accordance with the evidence afforded by the structural features of the Upper Siwalik, the present Salt Range is believed to have been chiefly formed subsequent to the Nimadric period. The commencement of its reelevation may, however, date from the time of rejuvenation of the Himalayan Range, already mentioned as represented by the Upper

Siwalik gravels. There is evidence in these coarse gravels themselves, as now exposed around the Salt Range, that their source was near.

Proof is lacking as to whether all of the Siwalik series was laid down on the Salt Range area, but the indications are that the whole series was deposited there, being later removed in large part by erosion. The Kamlial beds still cover considerable areas on the range, whereas the later divisions of the Siwalik outcrop regularly on the north flank and around the eastern end of the range. All divisions of the Siwalik take part and have great thickness in the sharp anticlinal and faulted offshoots of the range in the Jhelum District, like the Kharian, Rhotas, and Bakrala anticlines, which are undoubtedly post-Upper Siwalik in age. There is no evident reason for doubting that the Salt Range was in the main contemporaneous with these. The uplifting of the range must have been a long-continued process, however, involving first warping and then gradual overthrusting on the "salt marls." Moreover, there is evidence that some folding and faulting has taken place subsequent to the main thrusting. The consistent occurrence of the saline and gypseous formation beneath the overthrust along the foot of the range for a hundred miles or more is a remarkable feature. These deposits would provide a lubricating medium for the thrust, and it is probable that their presence as the basement is not to be explained by erosional uncovering during a hypothetical long epoch intervening between the late or post-Siwalik upwarping and the faulting, but rather by bed-thrusting on a gigantic scale. In any case, the conclusion may be drawn with a fair degree of assurance that the upper limb or main mass of the range, as we now see it, was raised at the end of the Nimadric period and subsequently—that is, largely during the Quaternary.

Appendix: Record of the Jhatla Well

LOCATION, STRUCTURE AND OBJECTIVE

Beginning in February, 1923, the Whitehall Petroleum Corporation, Limited, drilled the deep well before mentioned, north of the Salt Range. Its location was in the Gandial Ravine, 2¼ miles west-northwest of the village of Jhatla, 8 miles southwest of Talagang, and about 24 miles westward from Bhaun, the termination of the Mandra Branch Railway. The elevation of the surface at the well is 1,740 feet above sealevel. It was drilled on the summit of a broad anticline separated by the deep synclinal basin of the Soan River from the sharp anticline of the Khaur oil field, 30 miles to the north. The purpose of the well was to determine whether oil accumulations occurred here in the Nimadric system, as they do in the Khaur field, and its final objective was the base of that system and the top of the Nummulitic. It was completed, at a depth of 6,007 feet, in April, 1925, without obtaining more than traces of oil. The Nummulitic limestone was reached at 5,925 feet.

DRILLING METHODS AND CASING

The well was drilled with a combination cable and rotary rig to a depth of 4,401 feet, and from there on with a Sullivan diamond drill to a final depth of 6,007 feet. It was drilled with cable tools to 560 feet; thence by rotary to 775 feet; thence by cable to 1,328 feet; rotary to 3,711; cable to 3,756; rotary to 4,393, and lastly by cable to 4,401, prior to installing the diamond drill. Various sizes of casing were carried to the following depths: Twenty-inch casing was set at a depth of 514 feet; 15½-inch casing at 1,075 feet; 12½-inch set and cemented at 1,953 feet; 10-inch set and cemented at 2,894 feet; 8¼-inch set at 3,841 feet; 6¼-inch set and cemented at 4,400 feet; and 5⅛-inch set at 5,308 feet. The diameter of the hole at the bottom was four inches.

Deflection tests showed the well to be practically vertical at the depths tested, and there was no indication that it was not close to vertical throughout. Similar evidence was afforded by the horizontal stratification of the beds in the cores. The tests, considered accurate to within one or two degrees, gave a deflection of 1.5 degrees at a depth of 5,485 feet; the same at 5,645 feet, and 1 degree at 5,805 feet.

STRATIGRAPHY OF THE WELL

The Jhatla anticline is a broad dome in the Middle Siwalik beds, covering an area of over 30 square miles, and elongated in an east-northeast direction. On the crest the strata are virtually horizontal, but a dip of about two degrees is attained within a third of a mile, both to the north and to the south of the axis. Farther away the strata on the north flank increase in dip to about ten degrees and on the south to about three degrees. The well started at a horizon estimated by surface measurements in the vicinity to be approximately 1,100 feet above the base of the Middle Siwalik. The depth to the top of the Nummulitic was estimated to be between 5,000 and 6,100 feet, and a point between 5,600 and 6,100 feet was considered the most probable figure. In making this estimate the chief factor of uncertainty was not the thickness measurements of the formations exposed at the surface, but the problematical extent to which thickening and introduction of older beds of the Nimadric system might take place northward from the exposed section on the north flank of the Salt Range. Based on the thicknesses in the nearest sections to the south, the depth to the Nummulitic would be only 4,700 feet (lower part of the Middle Siwalik, 1,100 feet; Chinji, including transitional zone at base, 2,400 feet; Kamlial, 1,200 feet); but the Siwalik series increases in thickness northward toward the Himalayas, and, moreover, the Murree series, absent or thin in the outcrop along the Salt Range, was bound to enter in and also increase in thickness northward. Accordingly, the assumption was made that there would be a gradual thickening, roughly proportionate to the distance and the difference in thickness between the outcrops on the south and the next sections to the north, near the Khaur oil field, about 40 miles north of the Salt Range. The estimate considered most likely was as follows: Lower part of Middle Siwalik, 1,100 feet; Chinji beds, 2,890 feet; Kamlial-Murree, 1,700 to 2,080 feet, making the total depth from 5,690 to 6,060 feet.

The result of the well proved these measurements and assumptions to be close to the truth. The base of the Nimadric and top of the Nummulitic were reached in the well at a depth of 5,925 feet. No precise lines of separation exist between the various Nimadric stages, any more than they do on the surface, but the major divisions were well characterized and the dividing lines are taken to be as follows, on the basis of the general character of the beds as well as the examination of heavy residues: Base of Middle Siwalik at about 1,107 feet; base of Chinji at about 3,914 feet, the beds to here from about 3,636 feet being of the type transitional between Chinji and Kamlial; base of Kamlial-Murree, 5,925 feet. On the basis of this interpretation the Chinji in the well has a thickness of 2,807 feet, of which the lower 278 feet are transitional; and the combined Kamlial-Murree, between which no line can be drawn, is 2,011 feet thick. In addition, the well penetrated 82 feet deeper through the Eocene beds to a final depth of 6,007 feet.

In a boring of such depth it is interesting to note that the strata conformed in color, hardness, porosity, and other features, as well as in thickness, to the conditions observable in fresh exposures at the surface; also, in structure there was no sign of displacement of beds from their normal position and approximate horizontality. A slight progressive hardening was noted downward in the section, with increase in evidences of induration, such as small calcite veins and calcareous cementation, but these features may also be noted in surface sections, the tendency being for induration to increase gradually the older the beds are in the Nimadric system.

FOSSILS IN THE EOCENE

Samples from the depth of 5,925 down to the bottom of the well were submitted to Dr. W. L. F. Nuttall, at Cambridge University, for examination of the fossils. He kindly made slides and reported as follows:

> "The Foraminifera identified are small radiate *Nummulites* and *Dictyoconoides* cf. *conditi*, which indicate that these beds are of Eocene age. Ostracods as well as pelecypod and echinoderm fragments are also present. I am afraid that the fauna is too poor to venture an opinion whether the age of the limestone is Middle or Lower Eocene."

DESCRIPTION OF STRATA IN THE LOG

During the drilling (except for the first 300 feet) a geologist was constantly at hand to obtain and study samples of the material penetrated. The log was kept by Mr. W. F. Eastman down to a depth of 5,311 feet, and from there on by Mr. D. Dale Condit. The geologic section is, therefore, much more accurate than the ordinary "driller's log," but it must be born in mind that such a log at best has limitations, owing to the conditions of sampling. Below the depth of 4,401 feet, where coring with the diamond drill commenced, it is nearly exact, the core brought up intact aggregating over four-fifths of the depth drilled from there down, and the intervals of broken and lost core being subject to close interpretation. For the upper 4,400 feet, drilled with rotary and cable tools, chiefly rotary, the element of interpretation enters in to a greater degree and the detail of beds can not be so closely described. Generally speaking, through this upper 4,400 feet it was difficult to distinguish thin beds of sandstone or siltstone as separate entities and difficult to estimate precisely the proportion of fine and coarser sediment represented in a zone when the two alternate in thin layers or are mingled. It is believed that a bed of siltstone as much as four feet thick never failed to be recognized, but sandstone beds, unless somewhat thicker than that, were apt to be obscured in the rotary drilling, except when revealed by a change in hardness from the adjoining layers. However, in a relatively thick-bedded series such as we are dealing with, the log records the alternation of coarse and fine sediment with fairly close detail.

Certain explanations are desirable as to the descriptions given in the subjoined log. In accordance with the usage adopted in this paper, the term "siltstone" (abbreviated to sls.) is used instead of "clay" and "shale," inasmuch as it was found impossible to employ either of the latter terms truthfully or both of them with any consistent distinction. Similarly, the adjective "silty" is applied to some sandstone beds with respect to which the description "clayey" or "shaly" might with a certain amount of truth be applied. It denotes not so much fineness of the whole bed as an admixture of fine silt in the form of a matrix, or in lenses or layers, giving the bed a claylike toughness or occasionally an approach to shaly structure.

As regards color of the beds, the predominant color of the sandstone is gray, and where no color is mentioned an assumption of gray will be correct in the great majority of cases. In the case of the siltstone beds, they may be assumed to be of the shade of tile red characteristic of the associated siltstones in the particular part of the column where they occur. Beds of mingled sand and silt or of intermediate size of grain usually have an intermediate color, a paler shade than the fine siltstone. The term "reddish brown" denotes the dull reddish brown or tile color characteristic of the siltstone beds in the Middle Siwalik and of some of those in the Kamlial. The terms "red" or "reddish," where used in the log without qualifying adjective, denote the color characteristic of the Chinji siltstone, a tile red with an admixture of pinkish and yellow which gives it an orange hue and bright aspect. This color also occurs occasionally (both in the field and in the well) in the Middle Siwalik and the Kamlial.

The beds are notable for their usual lack of coarse material. The terms fine, medium, and coarse are used as comparative terms with relation to the usual texture of the sandstone of the system itself. Of the sandstone designated "coarse" the major portion of the grains would range between one-half and 1 millimeter in diameter, with a minority of grains ranging up to 1½ and 2 millimeters. It is noteworthy that no really coarse sandstone, nor conglomerate of pebbles extraneous to the Nimadric system, was detected in the well, except the basal rubble overlying the Nummulitic.

Calcareous cement is present throughout, and all samples tested gave a strong effervescence in hydrochloric acid. Porosity tests made by D. Dale Condit of core samples of the Kamlial-Murree sandstones, and numerous tests of the same which were kindly made by Mr. A. F. Melcher, showed a porosity range of from 8 to 17.5 per cent by volume in the "fine" to "medium coarse" grained sandstones. The density of the specimens examined ranged from 2.68 to 2.71, with an average of 2.69. Samples of fresh sandstones taken from outcrops of the Murree and Siwalik showed approximately similar porosities, with a tendency to increased porosity where the calcareous cement had been leached out.

TEMPERATURES IN THE WELL

On the basis of the data mentioned below, the temperature at the bottom of the Jhatla well, at the depth of 6,007 feet, or 4,267 feet below sealevel, was approximately 172 degrees Fahrenheit. This gives a temperature gradient of one degree for each 49⅓ feet, if we assume 50 degrees Fahrenheit as the surface temperature of the ground.

The mud bailed from the bottom of the well when it had reached about 3,740 feet showed a temperature of 110 degrees Fahrenheit when brought to the surface in the bailer. It undoubtedly lost heat on the way up through the well. Assuming such loss as ten degrees, and it was probably more, this would give 120 degrees Fahrenheit as a minimum estimate for that depth. Such temperature would represent a gradient of one degree for each 53 to 54 feet on an assumption of 50 degrees as the surface temperature. A better basis is afforded by temperatures taken with a deep-sea thermometer after completion of the well, but the figures can not be considered as accurately corresponding to the depths because the hole was full of water. The measurements were as follows:

Depth in feet	Temperature in degrees Fahrenheit
2,780	115
3,210	127.4
3,860	134.6
4,380	140
5,820	168.4

The last figure is doubtless nearly correct for that horizon, being only 187 feet above the bottom of the well, but it is believed certain that the figures for the higher levels are excessive, owing to the water in the hole being influenced by the bottom temperatures. The temperature of 168.4 degrees Fahrenheit for 5,820 feet gives a temperature gradient of one degree for each 49 feet, assuming 50 degrees as the surface temperature. It is possible to arrive at a close figure for the temperature at the bottom of the well, at 6,007 feet, by projecting below 5,820 feet the curve of increasing temperatures afforded by the above figures. The average increase between the measurements at 2,780 feet and 5,820 feet is one degree for each 56.9 feet. At the same rate the temperature at 6,007 feet would be 171.7 degrees. The increase between the measurements of 4,380 and 5,820 feet is more applicable and also believed to be nearer normal, being one degree for a little less than 51 feet, and projecting this downward for the balance of 187 feet gives a figure of 172 degrees for the bottom.

Additional, although less precise, evidence of the underground heat was afforded by the artesian flows that were met in the course of drilling.

The water from the 3,658-foot horizon had a temperature of 80 degrees Fahrenheit as it flowed out at the surface. The 3,820-foot water had a temperature at the well head of 95 degrees Fahrenheit, and later, when the flow from these two horizons mingled, the temperature was 90 degrees Fahrenheit. In the case of both the water was certainly much cooled on the way up.

OCCURRENCE OF WATER IN THE WELL

Stratigraphic range of artesian flows.—Artesian flows of water were encountered in six or seven sandstone horizons in the well, the water being in all cases sweet and potable and of meteoric rather than connate origin. It was found satisfactory for drinking and for use in the boilers and supplied all needs of the camp. The water in several horizons gave much trouble in the drilling, being under such heavy pressure as to prevent its being mudded off. Such flows were expected under the structural conditions prevailing here, with the porous beds rising a few miles to the south and outcropping at the edge of the basin at elevations slightly higher than the site of the well. It was a matter of some surprise that more such flows were not met. The upper four horizons were in the Middle Siwalik, above a depth of 900 feet. The next two horizons (numbers 5 and 6, as listed later) were about 3,000 feet deeper, below the main mass of the fine-grained Chinji formation, within the zone, about 250 feet thick, which may be considered as transitional between the Chinji above and the coarser Kamlial below. With one possible exception (horizon 7, as listed later), the failure to find important water sands within the Kamlial, where they might have been expected most of all, is noteworthy, inasmuch as approximately 1,000 feet of these predominantly sandstone beds outcrop on the north flank of the Salt Range, on the south edge of the basin, as just mentioned, and are not only exposed to a fair rainfall (about 15 to 30 inches per annum), but are crossed at right angles by numerous rivulets that descend the ravines of the Salt Range. A probable explanation of the lack of notable water sands in the Kamlial is that many of these sandstone beds, throughout the thickness of the formation on the north flank of the Salt Range, show an impregnation with oil at their outcrop. This may act as a seal in the case of the more porous beds, preventing their absorbing surface waters. Evidence in support of such an explanation is afforded by the Ghabir River well, drilled by the Attock Oil Company near the foot of the Salt Range, three miles southwestward from the Jhatla well. It penetrated the basal few hundred feet of Chinji beds and the whole of the Kamlial, where they are dipping 11 to 12 degrees northward off the

Salt Range, and is reported to have found practically no water in either formation, whereas several tar sands were met. On the other hand, an artesian flow of water (acid and saline), with a closed pressure of 200 pounds per square inch, was reported in the upper part of the similarly northward-dipping Nummulitic limestone series below. In the Jhatla well the latter was not found water-bearing.

The water horizons.—The occurrences of water were as follows:

1. Depth, 44 feet; a small stream of water from sandstone.
2. Depth, 160-165 feet; approximately 420 gallons an hour.
3. Depth, 370-377 feet; minor influx of water.
4. Depth, 850-860 feet; roughly 250 gallons an hour. The combined flow from horizons 2, 3, and 4 for the first month after horizon 4 was encountered was between 600 and 670 gallons per hour A year later it was between 550 and 600 gallons.
5. Depth. 3.658 to 3,673 feet; initial flow at rate of over 4.000 gallons per hour, declining within a few hours to 670 gallons per hour and to about 400 gallons per hour after two days. This rate continued nearly three weeks, but then declined at the end of the first month to 325 gallons per hour. At the end of the second month the flow was 270 gallons per hour and four and a half months after it was struck the flow had declined to about 150 gallons per hour.

   During the first few weeks at least this water was under a pressure of about 500 pounds per square inch at the well head. After two months, although it was not measured. there were indications of the pressure being reduced about 40 per cent.
6. Depth somewhat less than 3.841 feet, probably from the thick zone of gray sandstone at about 3,820 feet. The original flow was 1,400 gallons per hour and the established flow for the first month approximately 1,250 gallons per hour. After two months it was about 1,130 gallons per hour. After four months (over six months from the date of horizon 5) the combined flow from this and horizon 5 was 1,200 gallons per hour, and the yield of these continued to supply the drilling camp with water for all purposes until the well was abandoned (more than sixteen months from the date of horizon 5).

   The pressure of this water at the well head was measured as at least 480 pounds per square inch and probably something more.
7. At a depth between 4,350 and 4,400 feet there may have been a water sand yielding a flow of about 250 gallons an hour. There appeared to be an increment of about that amount to the flow from horizons 5 and 6, but owing to the drilling conditions the flow from 5 and 6 was subject to fluctuations, and circumstances did not permit a definite determination as to whether a new flow was struck here. In any case there was no change in the character of the water.

Other beds containing considerable water may possibly have been passed through, but artesian flows were not detected at any point except those mentioned, and it is not believed that any major source was missed.

In the portion of the well below 4,400 feet the coarser sandstone beds were generally found to be moist, but the finer beds, on the contrary, almost dry.

Cause of pressure of artesian flows.—The pressure of about 500 pounds per square inch, measured at the well head, in the case of the water from horizon number 5 from 3,658 feet, and similarly in the case of the 3,820-foot horizon (number 6), was abnormally high, considering the elevation of the source beds at their outcrop. In noting this, Mr. Eastman reported that "at no other place sufficiently close to Jhatla to influence the pressure of artesian waters here do the Kamlial formation and the sands just above the Kamlial attain the height and consequent artesian head that obtains along the Salt Range. We must look, therefore, for factors other than artesian head to explain the excessive pressure." He inclined to the view that the water sands were comparable with quicksand, and that the water was for a time squeezed out under "rock pressure" when the well opened a vent. Mr. Condit made the following interesting comments and suggestion of one possible explanation:

> "The water pressures recorded are at least 300 pounds in excess of what would be expected were they due merely to normal hydrostatic head. The surface at the well is 1,740 feet in elevation and the nearest outcrops of Kamlial and lower Chinji to the south are at about 2,100 feet in the valley floors cut through the formations, giving a head of only 360 feet, which would normally account for about 160 pounds pressure. The water column for a pressure of 500 pounds would be about 1,135 feet, which, added to the elevation at the well, gives 2,975 feet. This is the approximate elevation of the Kamlial beds in the several places where they extend up the dip slopes to the crest of the Salt Range adjacent to Jhatla.
>
> "Such coincidence in the height of the Kamlial beds on the crest of the Salt Range with the height required to give the head registered at Jhatla suggests that the water pressure may be an 'inherited' one—that is, handed down from the time when the Kamlial and overlying formations had not been denuded from the higher portions of the Salt Range. Possibly the waters in the rocks beneath Jhatla may have been 'locked up' through partial cementation of the interspaces in the sandstones up the dip near the outcrop, thus preventing adjustment of pressure that would normally follow as erosion of the water-bearing beds from the upper slopes of the Salt Range proceeded. If this explanation is true, it should follow that the pressure and volume of water from the well will gradually decrease. . . . The amount of gas issuing at any time has been too slight to assume that it has any part in creating the pressure."

It is to be noted that the volume of the flows, and apparently also the pressure, did decline. Mr. Condit suggested filling of pore space in the strata near their outcrop through cementation by ground waters. It is also possible that oil acted as a sealing agency, and the hypothesis is rendered even more plausible by the fact that many of the beds of the Kamlial and lower Chinji may actually be observed at their outcrop as filled with oil residues. The oil has its source in the Nummulitic series and has migrated up through about 1,300 feet of beds, through the whole Kamlial and for at least 200 feet into the Chinji—that is, to just about the horizon of the artesian water sands in question. The idea that sealing by oil has acted to retain a super normal pressure of water in the lower beds of the Chinji may seem contradictory to the one previously suggested, that such sealing accounts for the scarcity of water in the Kamlial; but the seeming contradiction can be met by the highly probable assumption that the oil gathered in the Kamlial beds at an early stage of the Salt Range anticlinal folding before the beds were uncovered, whereas migration progressed upward into the Lower Chinji only at a later stage, after deformation and erosion had proceeded further and after the latter had become exposed to meteoric agencies. It is to be noted that superficial cementation of the exposed beds, with oil or otherwise, would have to be a continuing process concurrent with erosion and sufficiently in advance of erosion to prevent escape of the water. This does not appear an improbable condition, especially if oil is considered as the cementing agency.

In conclusion, it should be added that the above "inherited pressure" hypothesis is only put forward as an interesting and suggestive possibility. Evidence is not at hand to prove what is the true explanation of the pressure observed in these artesian flows.

Character of the water.—The water from all horizons was clear, suitable for drinking and use in the boilers, and not varying greatly in character.

I. An analysis of the mingled water from horizons 2 and 3 (160 and 370 feet) and a separate analysis of that from horizon 4 (850 feet) showed them approximately alike, as follows:

Basic Radicles in Solution	*Acid Radicles in Solution*
Na, K in excess of strong acids.	Cl and SO_4 in about equal amounts.
Some Ca.	Considerable CO_3.
Trace of Mg.	

A trace of organic matter. No silicic acid, Al, Fe, nitrates, nor nitrites.
Primary salinity (bulk).
Secondary alkalinity.
Primary alkalinity (slight).

Weight of Total Salts in Solution

Horizons 2 and 3: 100 cubic centimeters of water, brown residue .064 gram.
Horizon 4: 100 cubic centimeters of water, brown residue, .086 gram.

II. The following are analyses of the water from horizons 5 (3,658 feet) and 6 (3,820 feet):

	Horizon 5		Horizon 6	
Total solids per 100 cubic centimeters	.181 gram (approximate). Residue brown on evaporation. Some organic matter probably present.		.178 gram (approximate). Residue white.	
	Per cent weight.	Value.	Per cent weight.	Value.
Cl'	33.5	.9497	21.5	.6063
SO_4''	16.3	.3432	15.9	.3307
CO_3''	10.9	.3629	21.8	.7259
Total acid radicles		1.6508	....	1.6629
Na', K	38.3	1.6617	39.6	1.7226
Ca''	traces		traces	
Mg''	traces		traces	
Total basic radicles		1.6617		1.7226
SiO_2	.7		.3	
Iron	traces		traces	
Al_2O_3, nitrates or nitrites	none		none	
Primary salinity	68.		42.	
Primary alkalinity	21.		57.	
Secondary alkalinity	trace		trace	

LOG OF JHATLA WELL

In reading the log of the Jhatla well the following abbreviations are used:

(Ss. = sandstone; sls. = siltstone; "pseudo-congl." = "pseudo-conglomerate"; calc. = calcareous; rd. br. = reddish brown; purpl. br. = purplish brown.)

Depth in feet		Thickness in feet	
From	To		
0	9	9	Surface, coarse sand.
9	44	35	Reddish brown siltstone.
44	90	46	Sandstone. Small stream of fresh water entering a little below 40 feet.
90	100	10	Compact sand and sls.
100	118	18	Ss.
118	135	17	Rd. br. sls.
135	160	25	Ss.
160	187	27	Compact sand. Well yielding about 10 barrels of fresh water per hour at 160 feet.
187	218	31	Ss.
218	230	12	Bluish sls.
230	265	35	Rd. br. sls.

Depth in feet		Thickness in feet	
From	To		
265	280	15	Bluish sls.
			(Down to 300 feet the description is based on the driller's log, prior to the arrival of a geologist to watch the results.)
280	302	22	Ss.
302	308	6	Rd. br. sls.
308	337	29	Sandy sls.
337	345	8	Fine-grained ss.
345	350	5	Coarse gray "pepper and salt" ss.
350	370	20	Gray silty ss.
370	376	6	Coarse gray ss. with fresh water.
376	410	34	Gray silty ss.
410	420	10	Gray "pepper and salt" ss. with some sls.
420	440	20	Gray silty ss.
440	465	25	Gray ss. with some sls.
465	480	15	Coarse gray ss.
480	496	16	Gray ss. with some sls.
496	500	4	Coarse gray ss.
500	518	18	Gray silty ss.
518	520	2	Coarse gray ss.
520	535	15	Gray silty ss.
535	550	15	Gray calcareous ss. with some sls.
550	560	10	Predominantly brown sls., but with streaks or lumps of gray ss.; resembles "pseudo-conglomerate."
560	605	45	Rd. br. sls. and ss.
605	620	15	Gray ss. with some red sls.
620	640	20	Rd. br. sls.
640	650	10	Gray calc. ss.
650	665	15	Rd. br. sls.
665	685	20	Silty ss.
685	715	30	Gray ss.
715	742	27	Hard, calc., silty ss.
742	762	20	Hard calc. ss. with streaks of rd. br. sls. Boulderlike inclusions of gray ss. and sls. "Pseudo-congl." in part.
762	775	13	"Pseudo-congl."
775	813	38	Rd. br. sandy sls. with streaks of "pseudo-congl." between 791 and 810 feet.
813	820	7	Gray, calc., sandy sls.
820	832	12	Rd. br. sandy sls. with some "pseudo-congl." between 825 and 830 feet.
832	836	4	Gray, calc., sandy sls.
836	837	1	Rd. br. sls.
837	840	3	Gray, calc., sandy sls.
840	845	5	Rd. br. sls.
845	850	5	Gray, calc., silty ss.

Depth in feet		Thickness in feet	
From	To		
850	860	10	Soft gray ss. Water sand. Flow roughly 6 barrels per hour of fresh water.
860	875	15	Gray to red, calc., sandy sls.
875	900	25	Gray, calc., silty ss. containing boulderlike inclusions of ss.
900	910	10	Rd. br. sandy sls.
910	918	8	Gray, calc., silty ss.
918	936	18	Rd. br. sls.
936	942	6	"Pseudo-congl." Red ss. matrix with angular pebbles of ss. and sls.
942	946	4	Red sandy sls.
946	970	24	Gray silty ss. with hard calc. streaks.
970	974	4	Chocolate-brown sls.
974	990	16	Gray, silty, calc. ss.
990	992	2	"Pseudo-congl." Gray ss. matrix with angular ss. and sls. pebbles.
992	994	2	White to gray calc. ss.
994	1,001	7	Chocolate-brown silty ss. with "pseudo-congl." streaks in upper part.
1,001	1,027	26	Gray, silty, calc. ss.
1,027	1,044	17	Reddish sls. grading to yellowish sandy sls.
1,044	1,107	63	Gray silty ss.
1,107	1,110	3	Yellowish sls.
1,110	1,148	38	Yellowish sandy sls.
1,148	1,153	5	Gray silty ss.
1,153	1,161	8	Red sls.
1,161	1,165	4	Sandy limestone (or calc. ss.).
1,165	1,175	10	Yellow to red sls.
1,175	1,179	4	Red sls.
1,179	1,195	16	Red "pseudo-congl." (small ss. and sls. pebbles in a silty matrix).
1,195	1,205	10	Yellow sandy sls. with pebbly streaks, like above.
1,205	1,220	15	Red sandy sls. with pebbly streaks, like above.
1,220	1,239	19	Yellow sandy sls.
1,239	1,267	28	Gray silty ss.
1,267	1,273	6	Grayish white sandy limestone.
1,273	1,278	5	Gray, calc., silty ss.
1,278	1,283	5	Red sls.
1,283	1,305	22	Yellow to red sls. with considerable gravel of ss. and sls. pebbles.
1,305	1,311	6	Gray, tough, silty, calc. ss.
1,311	1,320	9	Red sls.
1,320	1,325	5	Yellowish brown slightly sandy sls
1,325	1,328	3	Brown sandy sls.
1,328	1,358	30	Predominantly gray silty ss.
1,358	1,366	8	Ss. with streaks of red sls.

Depth in feet		Thickness in feet	
From	To		
1,366	1,395	29	Gray soft ss.
1,395	1,420	25	Red to gray sandy sls.
1,420	1,431	11	Gray ss.
1,431	1,436	5	Red to gray sandy sls.
1,436	1,443	7	Fine-grained gray ss.
1,443	1,455	12	Red sls.
1,455	1,459	4	Fine gray ss.
1,459	1,461	2	Red sls.
1,461	1,478	17	Fine to coarse gray ss.
1,478	1,481	3	Red sls.
1,481	1,497	16	Gray ss. (streaks of sls.?).
1,497	1,502	5	Red sls.
1,502	1,514	12	Coarse gray ss.
1,514	1,537	23	Soft red sls.
1,537	1,558	21	Sls. with streaks of ss.
1,558	1,563	5	Red sls. with pebbly layers.
1,563	1,653	90	Mainly red sls. with minor beds of ss. ranging up to probably not more than 2 to 3 feet thickness.
1,653	1,698	45	Dominantly red sls.
1,698	1,703	5	Red sls. with streaks of ss.
1,703	1,726	23	Red sls.
1,726	1,741	15	Ss. with streaks of sls.
1,741	1,785	44	Dominantly soft red sls.
1,785	1,857	72	Mainly red sls. with minor beds of ss.
1,857	1,870	13	Ss. with minor beds of sls.
1,870	1,878	8	Hard calc. sls.
1,878	1,902	24	Mainly fine ss. with minor beds of sls.
1,902	1,904	2	Tough pebbly sls. ("pseudo-congl.").
1,904	1,916	12	Ss.
1,916	1,921	5	Red sls.
1,921	1,926	5	Ss.
1,926	1,937	11	Sls. and ss.
1,937	1,960	23	Red sls. with some ss.
1,960	1,978	18	Fine gray ss.
1,978	2,005	27	Gray ss.
2,005	2,068	63	Red sls. with streaks of ss.
2,068	2,100	32	Gray ss. with streaks of sls.
2,100	2,122	22	Tough red sls. A light yellow sls. layer at 2,120 feet showed a slight amount of anhydrite on analysis.
2,122	2,155	33	Red sls. with streaks of ss.
2,155	2,161	6	Silty ss.
2,161	2,180	19	Red sls. with streaks of ss.
2,180	2,190	10	Tough, gray, fine ss.
2,190	2,221	31	Tough, red, nodular or "pseudo-conglomeratic" sls.
2,221	2,230	9	Soft red sls.
2,230	2,435	205	Red sls. with minor beds of ss.

Depth in feet		Thickness in feet	
From	To		
2,435	2,444	9	Sandy sls.
2,444	2,452	8	Gray ss.
2,452	2,470	18	Red sls. with minor beds of ss.
2,470	2,526	56	Dominantly red sls.
2,526	2,529	3	Extra hard, red, sandy sls.
2,529	2,542	13	Red sls.
2,542	2,552	10	Sandy red sls.
2,552	2,559	7	Tough red sls.
2,559	2,594	35	Gray fine ss. (with streaks of sls.?).
2,594	2,599	5	Fairly hard red sls.
2,599	2,631	32	Dominantly gray ss., fine.
2,631	2,725	94	Alternating beds of ss. and sls.
2,725	2,741	16	Red sls.
2,741	2,751	10	Red sls. with layers of ss.
2,751	2,760	9	Thin beds of ss. and sls.
2,760	2,774	14	Mainly ss. with layers of sls.
2,774	2,790	16	Hard, calc., red sls.
2,790	2,862	72	Dominantly red sls. with minor ss. beds between 2,824 and 2,852 feet.
2,862	2,894	32	Hard, calc., red sls.
2,894	2,924	30	Red sls.
2,924	2,932	8	Hard, brown, fine ss.
2,932	2,944	12	Soft red sls.
2,944	3,031	87	Generally hard, calc., red sls. with minor beds of tough calc. ss., "pseudo-congl." in part.
3,031	3,066	35	Gray silty ss. and sandy sls.
3,066	3,142	76	Red sls. with minor beds of ss.
3,142	3,144	2	Hard gray ss
3,144	3,186	42	Alternating thin beds of ss. and red sls.
3,186	3,214	28	Red sls. with minor beds of ss.
3,214	3,232	18	Hard, calc., gray ss.
3,232	3,329	97	Gray fine to medium grained calc. ss. interbedded with minor beds of sls.
3,329	3,384	55	Alternating thin beds of ss. and sls.
3,384	3,430	46	Mainly ss. with considerable sls.
3,430	3,465	35	Dominantly sls., red.
3,465	3,489	24	Red sls. with minor beds of ss.
3,489	3,520	31	Red sls.
3,520	3,528	8	Hard, red, sandy sls. Abundant calcite fragments indicate beds are veined. (No calcite higher up in well.)
3,528	3,550	22	Red sls. with considerable ss.
3,550	3,588	38	Hard, red sandy sls.; calcite fragments.
3,588	3,593	5	Hard, coarse, gray ss.
3,593	3,616	23	Alternating thin beds of ss. and sls.
3,616	3,636	20	Red sls. with considerable ss.
3.636	3,658	22	Mainly ss. with minor beds of sls.

Depth in feet		Thickness in feet	
From	To		
3,658	3,673	15	Coarse gray ss. yielding large flow of fresh water.
3,673	3,701	28	Mainly rd. br. sls. with minor beds of ss.
3,701	3,723	22	Medium-grained gray ss.
3,723	3,760	37	Rd. br. sls.
3,760	3,773	13	Gray ss.
3,773	3,827	54	Gray ss. with streaks of hard calc. sls. Easy drilling in ss.
3,827	3,849	22	Thin beds of ss. and sls. Hard drilling. Large flow of fresh water, probably from just above this zone.
3,849	3,856	7	Mainly rd. br. sls.
3,856	3,862	6	Mainly fine ss. with lesser amount of sls.
3,862	3,914	52	Hard rd. br. sls., sandy sls., and some interbedded ss.
3,914	3,922	8	Brown sandy sls.
3,922	3,925	3	Rd. br. sls. and hard ss. bed
3,925	3,943	18	Hard, fine-grained ss. and coarser soft ss.
3,943	4,021	78	Mainly ss. with lesser amount of sls. interbedded.
4,021	4,039	18	Alternating beds of sls and ss.
4,039	4,051	12	Predominantly gray ss.
4,051	4,055	4	Rd. br. sls.
4,055	4,076	21	Alternating ss. and sls.
4,076	4,108	32	Rd. br. sls.
4,108	4,115	7	Hard, fine, gray ss.
4,115	4,134	19	Brownish sls.
4,134	4,241	107	Soft zone of rd. br. sls. and gray ss.; no certainty which predominates.
4,241	4,248	7	Gray silty ss.
4,248	4,252	4	Rd. br. sls.
4,252	4,259	7	Fine-grained calc. ss.
4,259	4,319	60	Mainly medium-grained gray ss. with minor amount of brown sls.
4,319	4,323	4	Hard, fine-grained ss.
4,323	4,339	16	Alternating ss. and sls. (probably ss. predominates).
4,339	4,348	9	Mainly fine gray ss.
4,348	4,374	26	Alternating ss. and sls.
4,374	4,401	27	Mainly hard gray silty ss.
4,401	4,413	12	Hard, gray, medium-grained to coarse ss. (Diamond drilling and coring commences at 4,401 feet.)
4,413	4,416	3	Hard, gray, medium-grained to coarse ss. with streaks of purplish "pseudo-congl." made mostly of particles of sandy sls.
4,416	4,418	2	"Pseudo-congl."
4,418	4,424	6	Coarse gray ss. with 1 foot hard, fine. gray ss. in middle.
4,424	4,427	3	Hard gray sandy sls.
4,427	4,439	12	Hard gray silty ss. with streaks of "pseudo-congl." composed largely of sls. flakes.

Depth in feet		Thickness in feet	
From	To		
4,439	4,445	6	Hard gray silty ss. with streaks of rd. br. to purple sls. and "pseudo-congl."
4,445	4,450	5	Irregular purple sls. particles cemented in matrix of hard, bluish, sandy limestone.
4,450	4,459	9	Rd. br. to purple sandy sls.
4,459	4,462	3	Hard fine gray ss.
4,462	4,472	10	Alternating gray ss. and rd. br. sls.
4,472	4,531	59	Medium to coarse-grained ss., with thin partings of purple sls. and streaks of "pseudo-congl."
4,531	4,534	3	Soft, purple, silty ss.
4,534	4,542	8	Rd. br. sls. with streaks of "pseudo-congl."
4,542	4,544	2	Rd. br. silty ss.
4,544	4,563	19	Red sls. with lenses composed of pellets of same material.
4,563	4,587	24	Red to rd. br. sls., sandy in streaks; not so pebbly as above.
4,587	4,589	2	Rd. br. sls.
4,589	4,599	10	Very hard, dense ss.; purplish at top, gray at bottom.
4,599	4,611	12	Fairly hard rd. br. sls. with many streaks of sls. pellets. Full of calcite crystals near base.
4,611	4,622	11	Very hard, dense ss.; purplish grading into gray.
4,622	4,633	11	Rd. br. sls.
4,633	4,643	10	Hard, fine, gray ss. with streaks of purple sls.
4,643	4,647	4	Rd. br. to purple sandy sls.
4,647	4,665	18	Friable, coarse, gray ss.
4,665	4,732	67	Coarse- to medium-grained gray ss. with streaks of hard "pseudo-congl."
4,732	4,734	2	Hard, medium-grained, gray ss.
4,734	4,739	5	Hard calc., "pseudo-congl." sls. particles.
4,739	4,764	25	Red to rd. br. sandy sls.
4,764	4,780	16	Grayish purple silty ss. grading into ordinary gray ss.
4,780	4,795	15	Medium- to fine-grained gray ss.
4,795	4,804	9	Probably same ss. (Core lost in hole.)
4,804	4,817	13	Medium-grained gray ss.
4,817	4,864	47	Fine to coarse-grained gray ss. with streaks of "pseudo-congl." and brown sls.
4,864	4,879	15	Soft, rd. br. to purple sandy sls.
4,879	4,915	36	Medium-grained to coarse gray ss., with lenses of "pseudo-congl." composed of sls. particles in limestone matrix.
4,915	4,970	55	Coarse to medium-grained gray ss. with a few streaks of the "pseudo-congl." between 4,940 and 4,967 feet.
4,970	4,984	14	Rd. br. nodular sls.; greenish calcite stringers.
4,984	4,986	2	Probably calcareous ss.

Feet		Thickness in feet	
From	To		
4,986	4,998	12	Hard, dense, medium-grained, gray calc. ss. Stringers and nodules of white calcite and one or two angular inclusions of brown ss.
4,998	5,002	4	Rd. br., sandy, nodular sls.
5,002	5,007	5	Hard, calc. ss.
5,007	5,040	33	Medium-grained to fine gray ss. becoming coarser toward base. Finer ss. is hard and calc., coarser is soft and wet.
5,040	5,066	26	Coarse, soft and wet gray ss. with "pseudo-congl." at base.
5,066	5,084	18	Bluish sls. grading into rd. br. sls.
5,084	5,097	13	Red to rd. br. sls.; calc. nodules.
5,097	5,128	31	Same as above, grading down into purplish sls. with streaks of ss.
5,128	5,131	3	Gray to purplish brown, fine, silty ss.
5,131	5,149	18	Gray ss., in part coarse, but mainly fine, and in part with streaks of sls.
5,149	5,155	6	Rd. br. to purple sandy sls.
5,155	5,159	4	Brown silty ss.
5,159	5,224	65	Gray, coarse to medium-grained ss.; coarse ss. in upper part is noticeably wet; streaks of "pseudo-congl." in lower part.
5,224	5,239	15	Rd. br., nodular, sandy sls. grading down into the following.
5,239	5,243	4	Purpl. br. silty ss. with calcite stringers, this grades down into following.
5,243	5,271	28	Gray, mainly coarse ss. with irregular lenses of sls.
5,271	5,311	40	Gray, medium-grained to coarse ss.
5,311	5,316	5	Purpl. br. to gray, calc., silty ss. and "pseudo-congl." in which pebbles are mostly of soft brown sls.
5,316	5,326	10	Purpl. br. sls. with silty limestone nodules and sandy layers.
5,326	5,336	10	Sandy, finely micaceous sls.
5,336	5,345	9	Gray, medium coarse ss. with layers full of brown sls. particles and calc. pellets.
5,345	5,360	15	Gray, medium coarse ss. with scattered pellets of brown sls., much mica.
5,360	5,408	48	Gray, medium coarse ss.
5,408	5,413	5	Gray ss. with pellets of soft brown sls. and calc. sls., grades down into greenish and brown sls. with calc. pellets.
5,413	5,445	32	Purpl. br. to rd. br. and chocolate-colored sls., in part sandy and with scattered calc. pellets and nodules, slickensides noted in upper few feet.
5,445	5,486	41	Gray, and in upper part brownish, medium-grained ss., much dark mica between 5,456 and 5,472 feet.

Depth in feet From	 To	Thickness in feet	
5,486	5,506	20	Purpl. br. sls. in part sandy and with scattered calc nodules.
5,506	5,507	1	Brownish gray ss.
5,507	5,509	2	Greenish gray ss. with sls. pellets
5,509	5,515	6	Purpl. br. sandy sls. with green mottling in upper part
5,515	5,533	18	Rd. br. sls. with calc. pellets and a one foot layer of calc. sandy sls. at base.
5,533	5,540	7	Purpl. br. to grayish, minutely cross-bedded, silty ss
5,540	5,543	3	Brownish gray medium-grained ss.
5,543	5,544	1	Purpl. br. sls.
5,544	5,555	11	Purpl. br. medium-grained ss. with ferruginous sls band
5,555	5,575	20	Gray ss.; upper part medium-grained, lower part sub medium grained.
5,575	5,578	3	Purpl. br. sandy sls.
5,578	5,584	6	Gray, medium coarse to medium-grained ss, with brown sls pebbles in upper part.
5,584	5,586	2	Dark gray, fine-grained ss., minutely cross bedded
5,586	5,595	9	Gray, medium coarse-grained ss with scatte[illegible] of large and small sls. pebbles in upper 5 feet.
5,595	5,603	8	Gray medium coarse to fine-grained ss
5,603	5,605	2	Gray "pseudo-congl." with pebbles of grayish to purpl. br. calc. sls.
5,605	5,626	21	Gray, medium coarse to coarse-grained ss with few small scattered sls. pebbles.
5,626	5,638	12	Gray ss. with irregular "pseudo-congl" layers containing pebbles of sls. and calc. ss., thin coal film
5,638	5,639	1	Purpl. br., hard, sandy sls
5,639	5,644	5	Gray calc. ss. with "pseudo-congl" layers of mixed ss. and sls. pebbles; three inches brown sls. at base
5,644	5,656	12	Gray, medium coarse ss.
5,656	5,661	5	Purpl. br. calc. finely sandy sls. with calc pellets
5,661	5,666	5	Purpl. br. sandy sls.
5,666	5,674	8	Purpl. br. to grayish medium-grained ss with "pseudo-congl." streaks containing small calc pebbles
5,674	5,702	28	Purpl. br. sls. with a few green lump [illegible] sandy layers, and lime pellets.
5,702	5,720	18	Purpl. br. calc. sls., slightly sandy in some [illegible] with lime pellets, showing of non-inflammable [illegible]
5,720	5,724	4	Purpl. br. ss. with gray nodules of calc ss.
5,724	5,726	2	Purpl br. calc sls with gray lime pellets
5,726	5,742	16	No record; core lost in well.
5,742	5,761	19	Probably all purpl. br. sls.; only 10 feet of core obtained
5,761	5,763	2	Purpl. br. silty ss.
5,763	5,771	8	Gray ss. of medium to medium coarse grain with purpl br. mottling.